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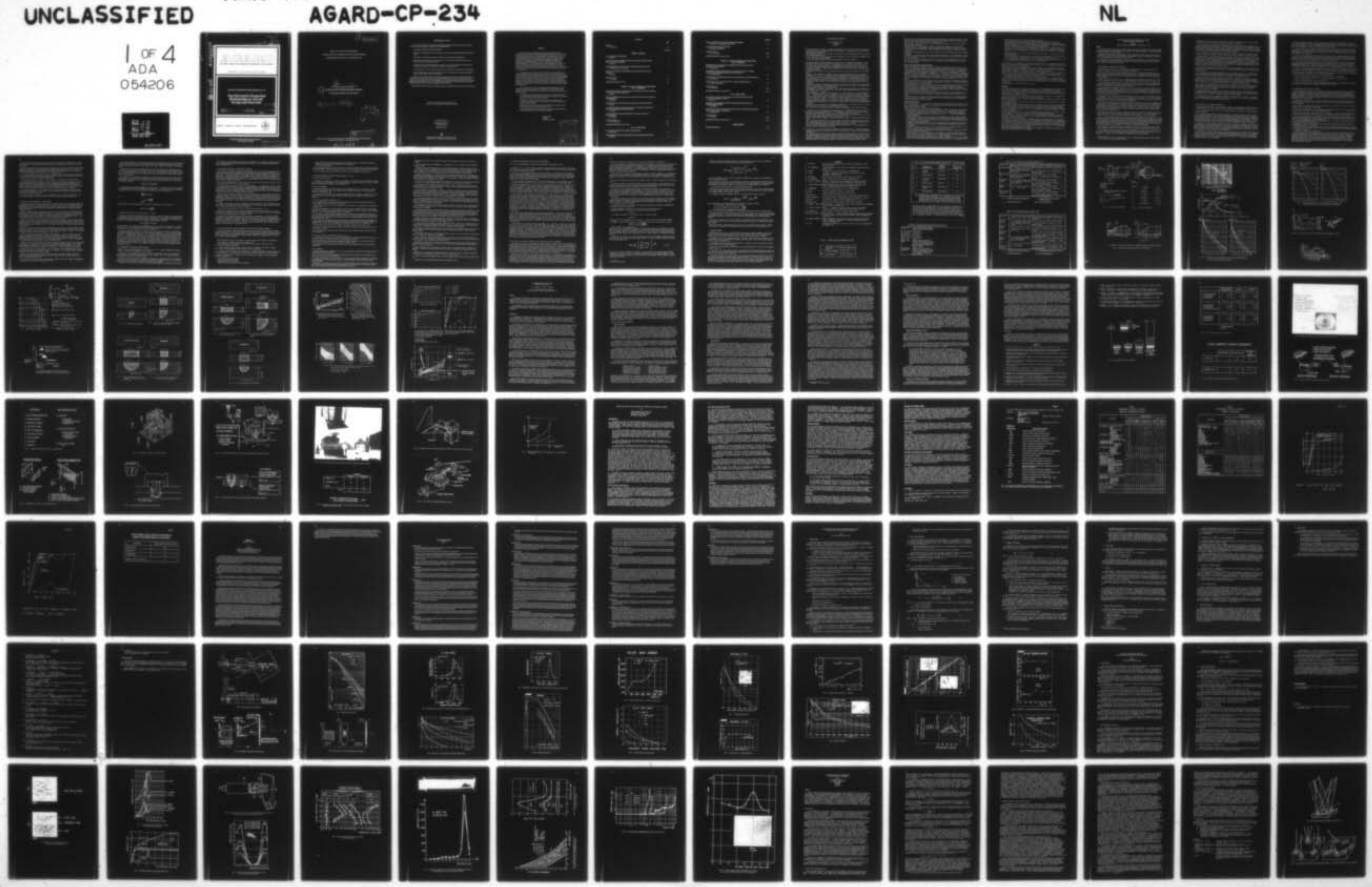

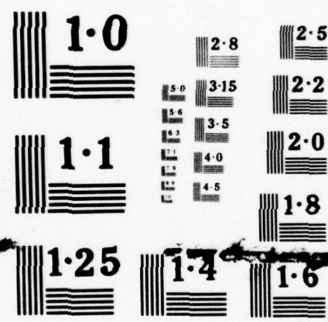

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Non-Destructive Inspection Relationships to Aircraft Design and Materials

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PREFACE

Non-destructive inspection (NDI) is a rapidly growing interdisciplinary activity representing one of the major technical facets of quality and its assurance. Being an activity derived from physics research, it is not surprising that it developed along the years in a way not necessarily related to the needs of design engineers. Because the existence of poor communications and limited rate of integration among materials technologists, design engineers and NDI experts was realized by AGARD, the SMP took the initiative of organizing a Specialists' Meeting in Voss. Over one hundred persons from 13 NATO countries participated in the Voss Meeting, where 20 outstanding papers were given. They gave rise to deep discussions which made sufficiently clear the state of the art of NDI methods for materials of interest to the aerospace industry, the weak points of some methods used at present, and the trends of application of known NDI methods; a few new methods came into the picture.

As it appears from a study of the papers, the situation does not seem satisfactory for the NDI methods in the field of composite materials where much work remains to be done. Furthermore, NDI of ceramic materials envisaged for turbine engine hot components deserves special attention and requires the setting up of new methods. In the area of metallic materials, the trend is aimed at automatic inspection, development of smart sensors and in-process inspection. Last but not least, a few new methods which are now under consideration (low-angle neutron scattering, digitalized infrared thermography, tomography, acoustical emission, multifrequency eddy currents, very-high-frequency ultrasonic beam scattering) deserve appropriate consideration.

There are still areas where a better understanding between NDI specialists, aerospace designers and materials producers needs to be established. To deal with certain human problems, the expert knowledge of the psychologist may also be required. These areas may be outlined as follows:

- NDI specialists need to identify the gaps in the spectrum of available techniques, to derive methods for measuring the quality of bonds and the integrity of thick laminates and, also to reduce the cost of NDI of composites.
- Designers need to be able to tell inspectors where to look and provide better accessibility into airframe structures. They should also re-examine the possibility of designing in brittle materials.
- Materials producers need to define acceptance standards for both metallic and non-metallic materials, including the characterization of resins.
- Psychologists should determine the qualities which make a good inspector, dealing also with the problem of boredom arising from automation.

C.P.GALOTTO
Chairman
Conference Committee

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NDI TECHNIQUES IN AEROSPACE

by

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1. The main objective of this paper is to present realistically how the state of the art in the domain of non destructive inspection technology contributes fundamentally to the safety and reliability of aerospace structures and components.
The technological progress to be consistently utilized with cost-effectiveness needs criticism and problem oriented management action.
In this token, we will present mainly qualitative considerations, even if quantitative judgements based on n.d.i. technology are to be stressed.
A liaison with quality assurance techniques and procedures will also be advocated.

2. Structures and Materials Panels expressed his interest in n.d.i. methods about 10 years ago. A survey was initiated with the scope to gather first hand information on the practical application of n.d.i. by airlines, armed forces and industries. An AGARDograph has been produced reporting this Survey.
The ad hoc Working Group formed within the Panel subsequently decided that the survey approach could not possibly be exhaustive towards proper consideration of the problem facing such an important aspect of aerospace technology.
A more systematic and problem oriented approach was decided and a more ambitious work was thoroughly planned.
The work, initially designed as a handbook, took the title of "NDI Practices" and was published as AGARDgraph n° 201 in dec. 75. It comprises a series of monographies giving the physical background of each technique and illustrating with some details the equipment and the instrumentation involved. With the scope of giving a sort of practical guide, important topics such as personnel qualification and applicable standards are added. Practical examples of application in real environments are given. The AGARDograph has been the result of fully qualified and authoritative contribution from NATO Countries Specialists.
In presenting the different techniques and practices, as far as possible a distinction was made between methods to be considered of general application both at shop and at field level, and more advanced methods, including even those at a development phase.
The AGARDograph was released for publication with the remark that there was some lack of omogeinity between different parts, but it was hoped that it could form a useful background and guide for all technicians involved in n.d.i. practice.
As far as management is concerned, it was considered to be an important feature of this AGARDograph, to stress the principle that for every inspection a clear term of reference was needed, i.e. what to look for in every instance, taking full advantage of Laboratory tests and full seale fatigue experimentation during development phase. It was also clearly defined the concept that the definition of the inspection leading to an evaluation of the results in terms of safety and reliability is necessarily calling the cooperation between n.d.i. specialists with both engineering and laboratory specialists fully knowledgeable and experienced with the part to be inspected as far as material and configuration are concerned.
As a matter of fact this principle is now generally accepted and it is significant that now in literature the most used term referred to is NON DESTRUCTIVE EVALUATION.
It is clear that the term evaluation implies a quantitative assessment and an operative decision.

3. In the same time the Panel implemented the important activity of FRACTURE MECHANICS Working Group. The importance of this working group needs not to be emphasized; at this moment we would like to pinpoint the fact that Fracture Mechanics and n.d.i. are two technologies strictly interrelated.
The modern trend toward higher strength materials, and higher applied stresses will often have a tendency to increase a structure's sensitivity to the presence of flaws.
Applied fracture mechanics attempts to provide techniques and criteria to produce damage tolerant structures.
N.d.i. techniques are practically the only means leading to quantitative assesments necessary to fracture mechanics application in order to perform a predictive analysis : initial flaw size and orientation, minimum flaw dimensions, and flaw growth pattern to the precritical stage.
The Panel provided the necessary liaison between fracture mechanics and n.d.i. working groups and it was felt that this liaison had positive results.

4. The remark that fracture mechanics requires quantitative assessments from n.d.i. techniques has been leading to the fact that at this moment and in this connection the most used term used is NON DESTRUCTIVE EVALUATION.
Very intense experimental work has been conducted to quantify precisely flaw-detection capabilities of any given NDE technique and statistical methods have been applied to demonstrate the validity of these capabilities. Samples with known flaws (artificially grown fatigue crack) of various sizes are been thoroughly inspected; the statistical analysis of the detection results have been made to determine the crack size range for which 90-percent probability of detection at a 95-percent confidence level.

Results of these reviews produced estimated curves of "design values" for reliable detection of crack-like flaws. As a term of reference we quote the quantitative estimation presented in "Fracture control methods for space vehicles" NASA CR-134597, issued Aug. 1974.
At this level of logic we will referer to the recent MIL-A-83444 (USAF) 2 July 1974 title "Airplane damage tolerance requirements".
This specification will be discussed in a paper by an authoritative speaker in this conference.
In this specification detailed damage tolerance requirements are specified as a function of design concept and degree of inspectability, being both design concepts and degrees of inspectability properly defined.
Initial flaws are assumed to exists as a result of material and structure manufacturing and processing operations.
We consider to be assumed that the initial flaw dimensions referred to in this specification are consistent with the result of experimental and statistical work as pointed out in NASA CR-134597 just taken as a term of reference.
We will not be involved in further discussion of this point, but from a management point of view we feel that some qualitative considerations are to be put forward for sake of both safety-reliability and cost effectiveness.

5. QUALITY CONTROL AND QUALITY ASSURANCE ASPECTS

Aircraft and components are manufactured using raw materials and semifinish products which are the result of an industrial process. This process is adequately specified and monitored; its variability is experimentally determined thru the quality assurance techniques and procedures. The outgoing product characterization in terms of measurable parameters is the objective of a requirement specification.
Quoting from the article "Standards of acceptance by n.d.i. inspection for raw materials and components" by Herbert F. Campbell that appears in the AGARDograph 201, "the ideal result is a procurement document which (i) identifies characteristic critical to the design function, (ii) specifies accurately the characteristic requirement, (iii) provides the test methods for determining compliance with the requirements".
The flaws in the materials do not just happen : their origin and quantitative characterization comes from the variability of the process. Eventually these data are injected into the conceptual engineering process presented for ex. in the MIL-A-83444.
In the present state of the art the evidence of full connection and consistency within all these phases taking into account the necessary trade-off seems not to be optimized and possibly finalized.
The intensive work of this harmonization between materials procurement, engineering specifications, structures manufacturing, and monitoring of structures during service life is in our opinion the main problem facing technological management in our field.
Certainly some efforts are being currently produced in this direction but we feel that much is yet to be done. We are confident from this conference a comprehensive program of Quality Assurance will be issued.
Within the frame of this program non destructive inspection and evaluation will be properly situated, avoiding duplications and possible lack of selectivity of activities. Quality control documentation will give traceability of the whole process.

Degree of inspectability

The concept is certainly to be accepted that a structure is to be monitored during its service life by means of appropriate n.d.i. techniques. This procedure can assure safety and reliability and it is the result of mature modern technology.
We feel however that some conditions should be fulfilled.

1) In any case every n.d.i. should be performed following the direction of a specific technical order.
2) For monitoring of structures condition during Service life, n.d.i. instructions will be issued covering critical items demonstrated at laboratory level and/or accepted following damage tolerance design requirements. But these critical items are to be cl... ...tated and the inspections properly programmed.
   The efficiency of inspections is highly improved if the inspector knows exactly what is looking for. Furthermore, the sensitivity of many of the inspections methods is highly dependent upon previous knowledge of crack orientation. Knowledge with a strong suspicion are the most important contributors for all inspection methods.
   A programmed inspection during service life, of course implies suitable accessibility of items to be inspected, and this fact is to be considered at design stages when degrees of inspectability are indicated.
   To improve the present state of the art it is to be advocated positive improvement in n.d.i. techniques to be used to inspect fasteners holes without removal of fasteners.
   It is furthermore remarked that the intervals between inspections are to be acceptable in terms of operational readiness of the aircraft.
   We cannot conceal our concern when we hear about structures to be inspected between flights or within intervals of let's say 5 flights; we will not comment possible requirements of monitoring critical items during flights thru automatic n.d.i. visually displayed.
   These practices could hardly be accepted outside the phase of development of a new a/c: as a matter of fact not only these requirements would interfere with the availability of a/c concerned but they

would be an indicator of poor safety and of basic unreliability.
Such procedures could not be accepted as a correct maintenance philosophy at field level.
Our purpose in putting forward these considerations in this paragraph is to draw the attention that full benefit of n.d.i. can be reached harmonizing quality assurance - engineering requirements-maintenance programs thru intelligent and far reaching management action.
It is, as a last consideration, to be remembered that, in a positive n.d.i. program, experience of human errors is to be accounted for.N.d.i. operators and inspectors are assumed to be duly qualified; their activity is also assumed to be kept under constant control at higher level of responsability.
Experience suggests to point out that typical human errors are likely to occur both at shop and at maintenance level.
At shop level the most frequent human error come from routine boreness and from psycological saturation. At maintenance level most errors come from adverse environment conditions.
It is a responsability at managerial level to take all measures to minimize the possibility of human errors and to provide for intelligent double checks as necessary.

6. Up to this point in our presentation we have implicity assumed that n.d.i. requirements are oriented to protect the structures from fatigue damage in metallic materials. This is a fundamental aspect but other aspects are certainly not to be disregarded.
In this survey we think deserving special mention highly accurate thickness measurement of conductive and non-conductive materials, measurement of case depth on material that have been case-conditioned and generally check on geometry and surface conditions, including weld seam tracking.
We will mention also some n.d.i. applications typical in maintenance activity : for ex. internal conditions of tubes, corrosion tests and checks of geometry or configuration in unaccessible areas.
As far as composite and non metallic materials are concerned n.d.i. can provide the possibility of test requiring particular approach for prevention of structural failure.
In this meeting authoritative specialists will deal with these aspects of n.d.i. establishing common ground in the major disciplines involved (materials developement and fabrication processes, failure prevention, design criteria, standardization) and their interrelationship in the context of non destructive evaluation.
A special paper will discuss unfulfilled needs in n.d.i.

7. CONCLUSION

The quality assurance and control activities are known to be the basic management tool for modern industry to meet the contractual requirements and assuring safety and reliability of the product.
In this system for every phase of activity it is required a term of reference precise and objective; in aerospace the role of actions oriented to prevent structural failure and to quantify reliability characteristics are of paramount importance.
N.d.i. is foundation of Q.A. in our field; the state of the art and the diversity of techniques and instrumentation permits to come in every case to operative assesments.
Many technical improvements are in development phase and no doubt that interesting results will be reached in a near future.
Our main concern however at this moment is to stress that the most significant progress is to be expected in management areas.
Manufacturing of raw and semi-finish materials is to be performed according to technical specifications defining outgoing quality, accurately and unambiguously according to requirements issued by design authority. The conformance to these requirements is to be demonstrated thru Q.A. documentation issued by the qualified material supplier. N.d.i. is the main support and discriminating factor of this certificate of conformance.
This fact implies that there will be a set of standards-equipment-procedures to be followed by the supplier of material and not to be duplicated by the airframe or components manufacturer.
By this manufacture a different but consistent set of standards-equipment-procedures is applicable specifically oriented to detect and control the typical defects that can be induced during each phase of airframe and component fabrication.
In maintenance at field level a third set of standards-equipment-processes would apply in accordance with program of maintenance decided upon according to design philosophy and results of development tests.
It is necessary that this program of maintenance is really feasible in the context of the operational readiness of the product taking into account the typical environmental conditions. In maintenance too sophisticated n.d.i. techniques are not to be easily accepted while these techniques will be of great advantage during materials development and production.
We feel that a discussion along these lines between the specialists in each particular field will produce a main term of reference for our profession.

CRITICAL REVIEW OF VARIOUS STRUCTURAL SAFETY CONCEPTS TAKING INTO ACCOUNT NDI METHODS(°)

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SUMMARY

This paper is mainly concerned with a critical review of the various structural safety concepts adopted during the aeronautical and space technology development, with particular emphasis to fatigue (acoustic inclusive) and recent fracture mechanics.

A comparison is made between the deterministic and the probabilistic point of view in the analysis of the loading condition and the structure behaviour and consequently between the deterministic and the probabilistic formulations of the structural safety concepts.

As a conclusion to these considerations an analysis is performed relatively to the present and the expected impact of the fracture mechanics in aerospace structure design philosophy and to the impact of N.D.I. methods on fracture mechanics analysis.

1. GENERAL REMARKS ON STRUCTURE SAFETY CONCEPTS

The definition of safety,[1], is: "The conservation of human life and its effectiveness, and the prevention of damage to items, consistent with mission requirements".

Among the various fields that are today concerned with safety, "Non Destructive Inspection" (N.D.I.) methods interest in particular structural safety as regards static, repeated and fatigue loading conditions. Such methods have an impact both on the formulation of design criteria and on the design and production methodologies.

Safety as defined in MIL STD 721,[1], is an engineering problem, without any specification in a deterministic or probabilistic problem. Of course, the same observation is valid for structural safety, too.

In the application, and particularly in the design application, structural safety is approached where deterministic and probabilistic components play roles of various importance due to the knowledge of the structural behaviour and loading and environmental conditions.

A complete probabilistic approach seems to be still far in the future. At present,it seems yet to be demonstrated that such an approach could be the best for a significant judgement of the safety margins of a certain structure in certain employ conditions. In any case, if several theoretical concepts for a complete probabilistic approach are developed or under way of development, the necessary experimental data are far from a suitable availability.

The safety level of a structure is obtained by means of a series of criteria and requirements that must be considered as a whole. In particular it is to be emphasized that the criteria such as, for instance, the ultimate factor of safety, are not exhaustive in themselves of the safety level, unless they are accompanied by the quality control or product assurance requirements.

The evolution of structural safety concepts from the early statements up today has been promoted mainly by improvements in the knowledge of the phenomena involved in the flight and by the fast enlargement of the environmental and loading conditions, in which the flight structure have been involved. To this enlargement both airplane and missile structure have been interested in a unified process of safety thinking clarification, even though neither types of structures have been analyzed so far with different numerical values of the various safety factors.

Beside the usual uncertainty on several quantities involved, such as material strength properties, geometrical dimensions, and so on,the simplest aerospace structural problem, i.e. the static strength of a structure, has a wide uncertainty on the applied loads and, in particular, on their distribution.

Thus, a fully deterministic approach, that would imply very narrow probability distributions of all the quantities involved, is not possible. From the early aeronautical designs,structural safety has been obtained from deterministic safety factors (implicit or explicit), which mainly reduced the probability of having loading conditions more severe than the ones used in the absence of reliable probabilistic description of the loading conditions and of the strength capabilities. Even though strengths in the static case show no great scatter because of the requirements in the material and manufacture acceptance.

When probabilistic descriptions of loads or strengths are available, an approach based also on probabilistic criteria is possible. This becomes necessary when either or both the data have a wide scatter.

A fully probabilistic approach where a total failure probability in a given time is calculated - by taking into account all the environmental and loading conditions to be withstood by the structure - is not applied at present , due to the inadequacy of several necessary statistical data.

(°) Paper included in a research supported by the Italian "Consiglio Nazionale delle Ricerche"(contratto C.N.R.-SAS n.76-0031, see also [8] and [20]).

Nevertheless, an evolution toward the probabilistic approach is observed in spite of the enlargement of the physical problems involved and requested data, (see for instance [2]).

The more recent of such enlargements is connected with fracture mechanics concept , which had to be included in the aerospace structure analysis. Fracture mechanics studies the residual strength of structures with defects and the growing of cracks or flaws from their initial dimensions up to critical ones at which fracture starts. The processes involved by these two aspects are very complicated, but a body of knowledge has been established through which designers can approach the problem.

In such an evolution , a primary role is played by N.D.I.methods. They give the possibility of measuring cracks, flaws and other defects,and their capabilities are to be considered in a statistical way.

Theoretical analysis, tests and non-destructive inspection involved in the fracture mechanics problems require a great lot of time and are very expensive. Therefore it is necessary to single out the parts of the structure which need a fracture mechanics analysis. This is made by means of 'Fracture Control'. A 'Fracture Control Plan' must be adopted to do it, and to perform the fracture analysis if necessary.'Fracture Control' is a new engineering discipline that interests design, fabrication, environmental control, inspection, maintenance, repair and verification. Beside the N.D.I. methods, the fracture control is the new practical aspect of the structure design of today.

In spite of the advancements in the non-destructive inspection methodologies, there is always a finite probability, for the large and complex structures, of test or operational failures due to the presence of undetected defects.

The "Fracture Control Plan" largely adopted at present in Aerospace Industries is an actual means to focus the engineering and workmanship attention on the problem of the existence of such defects in the structures, with the aim to reduce the probability of failure of the primary structure.

Several technical sectors having different responsibilities in the project of a vehicle, including design, analysis, tests, materials, fabrication, non-destructive inspection, are organized through the 'Fracture Control Plan' in a system which foresees a series of checks that allow the 'Project Management' timely to resolve the critical problems being discussed in the proper processing meetings.

Early location and evaluation of the fracture problems is essential to initiate corrective actions in terms of design configuration changes, structural materials selection and fracture control approach. A correct planning of all the fracture control activities is needed to ensure a proper integration with all the other design requirements.

A Fracture Control Board is established with engineering, product assurance, systems integration and tests,operations who are responsible for verifying that design and construction meet the agreed specified requirements.(As to the structural Integrity Program see also MIL-STD 1530).

The identification of parts or components selected for Fracture Control, on the basis of criticality for the flight-worthiness and susceptibility to cracking or fracture, is required as a basic element to establish a consistent and correct 'Fracture Control Plan'.

2. SAFETY CONCEPTS AT THE DAWNING OF AERONAUTICS

In 1900, Wilbur Wright wrote: "I am constructing my machine to sustain about five times my weight and I am testing every piece. I think there is no possible chance of its breaking while in the air",[3].

In 1911, P.James and Delaunay carried on flight tests to measure the loads on an aircraft due both to manoeuvre and gust,[4].

In 1912, H.Reissner made the first scientific treatment of aircraft stress analysis, which contained various proposals regarding the flight loading conditions and the suitable safety limits. He suggested an ultimate safety factor of 3 (both for tension and compression), permissible stress equal to 2/3 of the limit of elasticity stress (i.e. a 1.5 safety factor against the material yielding). Reissner indicated also the great importance of "toughness" (high difference between ultimate and yield stress) in the case of repeated tension loads as well as high limit of elasticity in compression (instability problems).

During World War I (and precisely 1913-1914), on the basis of Reissner's suggestions, Wilhelm Hoff in Germany measured in flight the force acting on the lift wire of an externally braced biplane. The data were published during 1922. The results of Hoff inspired German Regulations for the design and the acceptance of airplanes (1916 revised in 1918); no distinction was introduced between 'safety factor' and 'expected maximum load factor (having a specified probability)'.

In the twenties, flight tests were carried out by various investigators to determine the maximum acceleration of the airplane gravity center. Among them James Doolittle reported the value of 7.8 g (about 8) in a pull-out after a steep dive. On this basis it was stipulated that fighter planes could withstand an ultimate load factor of 12 (that implies a safety factor of about 1.5) . During gust tests maximum acceleration of about 2.5 g was encountered.

In 1926, following to a proposal of van Gries dated 1918, a provisional load assumption of the D.V.L. contained a clear subdivision into "load factors definitely required" and a "safety factor". A safety factor of 2.0 was suggested.. It was also requested that no residual deformation should remain after load removal (such requirement was also included in the German Regulations of 1924).

In 1931, R.V. Rhode and E.E. Loundquist published their study on the maximum loads due to gusts encountered in flight. The study described the V-n gust envelopes,which are now familiar, connecting the extreme combinations of flight velocity and vertical acceleration. In 1937 R.V. Rhode published the V-n record of about 20,000 hours of flying test.

In 1935 , after a publication of Küssner and Thalau dated 1932, M.G. Küssner treated the gust loads statistically and calculated the failure probability of a wing having a predetermined strength, without allowance for the probability distribution of this quantity. On the basis of the data concerning the Fokker D13 and the Junkers F-13, he gave 1,000 hours as a suitable design lifetime.

In 1939, Sir Alfred Pugsley estimated the safety of an airplane by means of the theory of probability, taking into account the statistical nature both of the applied loads and of the structural strength. He recommended an accident rate for the entire airplane of 10^{-5} each flying hour, and a rate of 10^{-7} as concerns structural failure alone. In 1942, Pugsley published a more detailed explanation of his proposal.

In 1945 , A.M. Freudenthal presented a detailed analysis of the statistical properties of the strength (from material tests) and a probabilistic approach to the safety problem of civil engineering structures.

During 1948 at the Third Congress of the International Association for Bridge and Structural Engineering, Various contributions of Congress, Prot, Levi, Cassé were registered.

In the fifties contributions of Pugsley, Tye, and Freudenthal were also registered.

In 1954, A.P. Kennedy used a value of 10^{-7} for the failure probability in one hour flight.

In 1955, Bo Lundberg proposed 10^{-9} for the same quantity.

In 1956, A.O. Payne carried out in Australia fatigue experimental tests on a large number of "Mustang" wings, taking into account also the beneficial effects of the pre-loading

3. THE DETERMINISTIC STRUCTURE SAFETY APPROACH

While the probabilistic aspects of the structural safety problem were already singled out and the first probabilistic approaches were proposed, the deterministic approach for static loads was improved and brought to considerably high level of quality so that together with the fatigue safety concepts it would constitute a good basis for aeronautics and space purposes. The whole set of such concepts, which were developed when static and fatigue loads seemed to be substantially disjoined from each other, was applied to manned aircraft for many years.

The deterministic approach for static loads is based on the definition of two main load levels: limit loads and ultimate loads. Probabilistic aspects are not absent in their determination but deterministic values are pursued.

Limit loads are the loading conditions which are expected to be encountered in flight and in the other operations within the prescribed flight envelopes.

Ultimate loads are obtained from limit loads by means of a multiplication factor, the 'ultimate safety factor', that is usually equal to 1.5 unless otherwise specified.

Roughly speaking structure is requested to sustain ultimate loads, to suffer no unacceptable deformations under limit loads and to suffer no permanent set or yielding after removal of limit loads.

In the previous requirements the more discussed figure was the ultimate safety factor, but the various authors gave different analysis but quite different criticisms. In the commonly adopted philosophy this factor in the early formulation of the approach must give:

- allowance for non-permanent set or yielding at limit load (i.e. must do very close between their requirement at ultimate and at limit load);
- allowance for defects in materials and processing (the more detailed analysis specifies thathere undetectable defects are to be intended);
- allowance for design uncertainties and inaccuracies due,for instance,to aeroelastic effects, fatigue, flutter, dynamic effects, structural complexity, loading spectraand load distribution, aerodynamics heating;
- allowance for stiffness;
- allowance for exceeding specified manoeuvres.

During the improvement of the knowledge and technical progress the various uncertainties before indicated were covered by a part requirements or data and that was the reason for several proposals of diminishing the ultimate safety factor. Up-to-day these proposals did not result in practical statements, exception being made for the values lower than 1.5 used in missiles and manned spacecraft. In their technology are determinant, beside the extreme weight saving necessities, several less severe environmental conditions and very accurate and expressive analysis and test methodologies to cover the more severe environmental conditions.

Limit loads are defined by flight conditions envelopes, such the manoeuvre diagram (fig.3.1) and the gust diagram (fig.3.2), and other specified conditions such as landing, crash, taxing and so on (see also fig.3.3).

Manoeuvre and landing loads have an input on the suggestion to the pilot as concerns the values of the appropriate parameter not to be exceeded during operational flight. The probability of such loads to be exceeded was evaluated and it constitutes a basis for a probabilistic approach (see, for instance, fig. 4.7). Also MIL requirements report data on such a probability (see [2]).

Gust loads were derived from statistical data of a phenomenon which cannot be defined in another manner. Gust velocities and the other data on which discrete gust loads are to be evaluated are the result of a choice of the limit load permitted in practical operation.

The ultimate safety factor introduces a strong reduction of the hazard of a structural failure.

Other important probabilistic aspects, involved in the so called deterministic approach, are the materials mechanical properties and data which are to be employed during structural calculations and materials evaluations. The data reported in the main handbooks result from statistical evaluations, [5], class "A" data have 90 per cent. probability, with 0.95 confidence level;class "B" data have 90 per cent. probability with 0,95 confidence level;class "S" data are simply minimum value for acceptance.

As reference indications of the statistical material and structure properties, we may mention the data reported by Freudenthal, [6], (see table 3.1) who indicated also the normal and log-normal distributions as the more appropriated ones.

As concerns materials an inspection of the consolidated data with a comparison between class A and class B values, seems to indicate also lower variations than the ones reported by Freudenthal.

4. STATISTICAL DATA AND PROBABILISTIC SAFETY APPROACH

An important change in the design philosophy was the probabilistic analysis of the applied loads. The probabilistic nature of gust loads was clear earlier in their introduction in the engineering field, but the description available as power spectrum of the root mean square and as function probability of the root mean square to be encountered in flight open new possibilities for structural analysis as far as both static and fatigue problems are concerned.

Available statistical data on gust power spectrum are in continuous evolution since the early comprehensive data of Press, Meadows and Madlock (see fig.4.1), [7], and for instance, the data reported by Etkin (see fig.4.2) [10], to the data to day available and quoted also by the Regulation (see [2]). Also the distribution of the root mean square of the gust velocity (see for instance figg.4.3 and 4.4., [7]) are continuously under revising process, due to new experimental data acquisition.

Analogous descriptions are today disposable and in continuum improvement as concerns various loading condition as the thrust of missile engines (instability effects), the roughness levels of various airfield preparation (see [2]) the cumulative occurrence of normal load factor experienced at the center of gravity during thousand runway landings (see [2]), the cumulative occurrence of sinking speed during thousand landings,and so on.

Recently it was evidentiated that the noise produced by various sources as turbo-jet or other engines, boundary layer and vortices (fig.4.5) gives not-disregardable acoustic inputs for several parts of missile and aircraft structures (see for instance fig.4.6). Such inputs create dynamics responses on the structures and fatigue problems as concerns life expectancy, (see also [8]).

Several years ago, the same manoeuvre loads have been analyzed in a statistical manner. The results are given for instance, beside the number of peaks in a given time,as probability of having peak load factors exceeding given values (fig.4.7) or the cumulative occurrence of peaks (or troughs) during a given flight time (see [9]). Such data indicate, as an interesting notation, that there is not zero exceedence of the design manoeuvre load factor due to the pilot manoeuvre action.

Fatigue is also a physical behaviour that implies a statistical description because of the great scatter it is effected by. This scatter is present also in the more simple elementary aspects as, for instance, rotating bending, and depends also on the still unknown nature of the fatigue damage. As long as one considers more complicated loading and geometrical conditions, the scatter becomes greater and greater.

The impossibility of having scale model tests and the dependence of the fatigue behaviour both from general and local geometrical characteristics makes very expensive in time and money to obtain experimental fatigue results on every new structure design.

Therefore the safety phylosophy against fatigue generated two main design concepts, safe life and fail-safe that was based mainly on deterministic factor, deduced from typical fatigue experimental analysis or practical considerations.

In the safe life concept the structure was requested to suffer no failure in a number of times (deterministic factor that was fixed in 4) the design life time.

In the fail-safe concept the structure was requested to have redundancies and to suffer no catastrophic failure after the failure of a single element, when subjected to reduced (deterministic factor) static loads in comparison with manoeuvre and gust normal limit loads, so making 'not probable' a 'catastrophic failure'.

Statistical data on the various loading conditions are useful to obtain, after the dynamic analysis (see [10]), statistical data on the appropriate load or stress and, from them, the probability distribution of appropriate quantities (as for instance the peak to trough difference) and their number in a given time of flight. The application of a correlating rule, allows to obtain the life time of the structure before a fatigue failure.

As a sample of a fully probabilistic approach of the safety problem let us consider a structural element subjected to static loads of known probability distribution g(A) and having a known failure load probability distribution f(F) (Fig.4.8). The probability that an applied load does not cause the failure of an element is given by

$$S=\int_{-\infty}^{+\infty} f(F)\,dF \int_{-\infty}^{+F} g(A)\,dA$$

In order to obtain the survival probability in a given time T, it is necessary to know the total number N of loads having the distribution g(A) which are applied during T. If we suppose, only for the mathematical derivation, that N, T can vary continuously if R(N) is the survival function, it is

$$\frac{dR}{dN}=-R\left(1-S\right),$$

and

$$R=e^{-\left(1-S\right)\frac{dN}{dT}T}.$$

When $(1-S)\frac{dN}{dT}T\ll 1$ an approximate expression of the survival probability in a given time T is

$$R=1-\left(1-S\right)\frac{dN}{dT}T$$

This formula may be used also for discrete values of N and T.

Another sample of probability approach may be the problem of a structural element having known probability distributions g(A,n) of fatigue failure number n of alternate load, in function of the amplitude A, and subjected to an alternating load whose (constant) amplitude has a known probability distribution f(A) (fig.4.9). The probability distribution of failure alternation number is given by:

$$\varphi(n)=\int_{-\infty}^{+\infty} g(A,n)\,f(A)\,dA$$

The same formula, in the hypothesis that the damage caused by each alternation of amplitude A is independent from the history of the previous alternation amplitudes, can be used if the element is subjected to alternations of non constant amplitude having the distribution f(A).

The proposed samples are sufficient to indicate that, in order to have fully prababilistic approaches of the safety problems, the difficult is not in the theoretical formulations. In a first analysis, it would seem that also the experimental data such as the involved probability distributions do not constitute a problem. A deeper analysis realized that the significativiness of the statistical figures for the safety is mainly connected with the reliability of those parts of the distribution curves which in a practical formulation can only be obtained by means of arbitrary hypothesis of the type of the probability distributions. At present, this make such figures unreliable. Furtherly, at the present state of the technology, the survival probability of a structural element in a given flight time is as near to unity that suitable differencies from a case to another are expressed by not self-evident differencies in the correspondent figures.

5. FAR REQUIREMENTS FOR TRANSPORT CATEGORY AIRPLANES

Beside the usual static requirements, FAR vol.3, Part 25 , [11] , includes requirements on "Fatigue Evaluation"; that are more interesting for this analysis.

"Those parts of the structure whose failure could result in catastrophic failure of the aeroplane" are requested to be evaluated under provisions of "failure strength", "fail safe strength" and-only for turbojet powered aircraft "sonic fatigue strength".

As concerns fatigue, the structure is requested to withstand the "repeated loads of variable magnitude expected in service" with reference to the "typical loading spectrum expected in service". It is possible to use correctly "service history of airplanes of similar structural design".

As concerns "fail-safe", after a failure of a single structural element, "catastrophic failure or excess-

ive deformation" of the remaining structure must be "not probable". This expression is substanzialized by static requirements which the remaining structure must withstand. They are reduced manoeuvre and gust static loading conditions.

6. DESIGN CRITERIA APPLICABLE TO A SPACE-SHUTTLE STRUCTURE

The structural safety criteria prepared for space-shuttle, [12], explicitly mention the probabilistic aspects of material mechanical properties which are indicated also by the up-to-date handbooks (see, for instance [5]). In particular, material values having a 90% non exceedance probability with 95% of confidence level are required to be used only in "redundant structure in which the failure of a component would result in a safe redistribution of applied loads to other load-carrying members". Materials values having a 99% non exceedance with 95% confidence "may be used whenever failure of a single load path would result in loss of structural integrity".

For brittle non-metallic materials "stress level to be used with limit loads shall not permit a probability of more than one failure in a million components".

As concerns the design aspects of fatigue and fracture mechanics, a fail-safe design concept is requested "where practicable". The fail-safe concept is actuated through the requirements that "the failure of a single principal structural component shall not degrade the strength or stiffness of the structure below that necessary to carry a specified percentage of limit load" and that the fatigue life of the remaining structure "shall exceed the time between scheduled inspections".

Safe-life design concepts are required for "all the structure critical to the integrity of the vehicle or personnel safety". The safe-life concept is actuated by requirements including regular inspection for the detection of flaws, and thus it could be better defined as a safe crack-grow-life concept. The flaws which cannot be detected in a regular inspection "should not grow enough before the next scheduled inspection to degrade the strength of the structure below that required to sustain" limit loads at critical temperature.

As concerns "sonic fatigue", cracks and catastrophic failure caused by the cracks themselves must be "not probable", assuming that the loads prescribed for "fail-safe strength", besides several other conditions, "are applied to those areas" which are interested.

In any case, "safe-life" must be "at least four times the specified service life".

Gust problem is approached both as discrete gust requirement and continuous turbulence. As concerns the probabilistic approach, the structure "shall be designed for a 1 per cent or lower risk of exceeding limit loads during the expected time of atmospheric flight".

As concerns safe-life design the so called "safe-life tests" are requested. For the design concepts which "depend on non-destructive inspections and flaw-growth predictions" such tests have the purpose of verifying on the structure with artificial flaws "the safe crack-growth prediction" and demonstrating that "non-destructive inspection techniques are adequate". For the design concepts which "depend on non-destructive inspection alone", safe-life tests have the purpose of demonstrating "that the techniques are adequate to ensure detection of significant defects".

7. UP-TO-DATE DESIGN CRITERIA (SAFETY REQUIREMENT FOR AIRPLANE STRUCTURE DAMAGE TOLERANCE)

The last few years made evident the necessity that the airplane safety of flight structure includes among his objectives, [13] , " to protect the safety of flight structure from potentially deleterious effects of materials, manufacturing and processing defects through proper material selection and control, control of stress level, use of fracture resistant design concepts, manufacturing and process control and the use of careful inspection procedure".

Safety requirements depend on two parameters: the design concept and the degree of inspectability.

Design concepts as considered today are indicated below, [13] .

- Slow crack-growth structure, where flaws or defects are not allowed to reach the critical size required for unstable propagation;

- Fail-Safe multiple load path structure, where structure is designed and fabricated in segments which contain localized damage and prevent complete loss of the structure;

- Fail-Safe crack arrest structure, where structure is designed and fabricated in such a way that unstable propagation will be stopped within a continuous area of the structure prior to complete failure.

Degrees of inspectability as considered today are indicated below, together with the corresponding inspection frequencies, [13] .

- In-flight evident. Once per flight.
- Ground evident. Once per flight.
- Walkaround. Once every ten flights.
- Special visual. Once per year or less if authorized.

- Depot or base level. Once every one quarter of the design life time. This inspection procedure may include NDI techniques and also foreseen removal of components.
- In service non-inspectable.

Safety requirements concern the intact structure in case of slow crack-growth structure, and both intact structure and remaining structure after the failure of the critical element in case of failsafe structure.

Two load levels P_{xx} and P_{yy} are introduced in order to give the requirements (see table 7.1).

8. DEFINITIONS AND DATA FOR UP-TO-DATE DESIGN CRITERIA (From [13])

8.1 Fracture critical structure

Two categories of fracture critical parts are considered in the specification:"those components or regions which are sized by the requirements" and "those components or regions which could be sized by the requirements if fracture control procedures are not employed", [13] .

8.2 General requirements

The safety of flight structure must comply with the requirements at least in a combination of design concepts and inspectability level. Such compliance must be demonstrated by means of all the necessary analytical and experimental work.

All fracture critical regions of all structural components must be inspected as a minimum with a close visual inspection for holes and cutouts and with ultrasonic, penetrant or magnetic inspection for the remainder.

8.3 Initial flaw assumptions (following [13])

Small imperfections due to material and structure manufacturing and processing operations,(Fig.8.1), shall be assumed to exist in each hole of each element.

Different (evidently lower) size can be negotiated if the contractor has developed initial quality data on fastener holes.

Besides small imperfections, no more than two initial flaws shall be assumed to exist in any separate element of the structure: one of them in the most critical hole and the other at the most critical location other than a hole. Interaction between them must be considered.

Initial flaw to be assumed depends on design concepts. As concerns slow crack-growth structure, flaw sizes are specified for hole and cutout locations, (fig.8.2), and other locations, (fig.8.3). Other surface flaw shapes,having the same initial stress intensity factor as the indicated shapes, can be considered as appropriate (see [13] , pag.3).

Small initial flaw sizes other than those specified for slow crack-growth structure may be assumed if it is demonstrated (by an NDI program approved by the procuring activity) that all flaws larger than the assumed ones have at least a 90 percent.probability of detection with a 95 percent. confidence level.

Smaller initial flaw sizes may be also assumed if proof-test inspection is used, [13] pag.4.

As concerns fail-safe structures,flaw sizes are specified for hole and cutout locations,(fig.8.4),and other locations, (fig.8.5).

Other possible surface flaw shapes with the same initial stress intensity factor (K) shall be considered as appropriate.

8.4 In-service inspection flaw assumptions (following [13])

If the component is removed from the assembly and inspected with the same procedure employed during the fabrication, the values indicated as initial flaw assumptions must be used.

When NDI techniques are applied without component or fastener removal, flaw sizes are specified for holes and cutouts locations,(fig.8.6), and for other locations, (fig.8.7).

Other possible surface flaw shapes with the same initial stress intensity factor shall be considered as appropriate.

9. NDI TECHNIQUES

Aerospace technologies has developed so far to a very high degree of sophistication, materials and test practices besides design philosophies.

This trend is due to the efforts devoted to weight saving and life predicting to a satisfactory level, taking into account overall cost-effectiveness.

At present, the improvement of the state-of-art is mainly concerned with the development of technologies of monitored production and processing of materials, fracture mechanics concepts and non-destructive inspection methods.

NDI methods are important also as facilities for the other two items. NDI are the means to enlarge, to several important material parameters,besides the geometrical ones,the analysis of the identity' between the service structural elements and those submitted to the various tests.

Materials are the result of an industrial process,and the presence of flaws must be realistically accepted.

A flaw can be defined as an inhomogeneity, a discontinuity or a local irregularity at microscopic or macroscopic level.

NDI must reliably provide detection of flaws and of their geometrical location and quantification. A question may arise if a detected flaw is to be considered a defect, and thus unacceptable. A flaw can incept a crack, and the utmost attention must be paid to the characteristics of fast-growing of small cracks (propagation), and to the previously existing notch effects leading to crack inception.

Detection and judgement are an uneasy basically and interdisciplinary commitment. Interpretation of NDI results should be delegated to a team of specialists rather than being left to the sole judgement of the NDI inspection. This team should be composed of a stress engineer, a material technologist, a laboratory expert and an NDI specialist, [14] , [15] .

In such a way, the terminology "non-destructive evaluation" is replacing the terminology "non-destructive inspection", to reflect changing emphasis and attitudes of the last few years, (see [14]).

This evaluation and the design/manufacturing practice are based on the modern concepts of fracture mechanics, which in its linear elastic approach is a stress intensity approach which establishes criteria for fracture instability in presence of a crack.

A basic assumption is the presence of cracks in the structure. The defect sizes which cause unstable fracture are related through theoretical and experimental data to the stress field at the crack tip, the applied stress and the material properties. In particular, flaws must be analyzed in order to evaluate the risk of a crack inception. Material properties, size and shape and orientation of flaws, design and stress analysis, work cycles are involved for a clear understanding of the problem.

Up-to-day maximum operating conditions, material requirements and meaningful inspection and acceptance criteria can be astablished to prevent brittle fractures in structures made of high strength materials. Methods for effective assessment of fracture resistance of the more ductile structural materials are also being developed into engineering methodologies.

The NDI methods are technical tools based on diversified physical principles. Some of these methods are routine at shop and laboratory level in both manufacturing and servicing fields. Other advanced methods are under way of development.

An integrated program of NDI fracture mechanics implies airplane design according to standards. It must be based on guiding rules to inspect of every component those parts having high risk character based on stress engineer's considerations. For each inspection the most appropriate method must be selected after assessing the capacity of the inspection method to detect the dimension of the least flaw considered significant on the grounds of the geometrical configuration and fabrication process.

A study, "Evaluation of Crack Detection Methods", conducted by AIT under ESA contract, collected and investigated data pertaining to crack-detection methods applicable to aerospace structures and recommended the most promising method or methods or further study, (see [15]).

In order to describe each method and provide comments about their capability, the following aspects are to be considered: operating environment (laboratory versus field), type of crack most readily detectable, minimum crack size detectable (detection sensitivity) and operational requirements.

The NDI methods of general application are: visual inspection, liquid penetrant, magnetic particles and magnetic rubber, X-ray and neutron radiography, gamma-ray radiography, ultrasonics, eddy current and acoustic emission.

The NDI methods applicable to laminated composite panels and joints are: liquid crystal, infrared reverberation, resonance and holographic interferometry.

To have a synthesis on the NDI method capabilities, one can refer to 'ad-hoc' publications (see, for instance [17] and [15]). Nevertheless, reporting here some data may give a picture of the stochastic nature of the knowledge in this field and of the state of the art.

The geometrical characteristics of the cracks to which the data are referred are the crack area or separately the crack length and the crack depth. A zone covered by the coupled length and depth observed in practice is indicated in fig.9.1.

A way of reporting data is the diagram of the "mean values or the confidence zones of the detection capability in function of the detection probability for given area interval and confidence level", (see fig.9.2).

Another way is the diagram of the detection capability in function of the crack length (or depth) for given probability and confidence level (see, for instance figg.9.3 and 9.4).

An idea of the available experimental data on which the proposed capabilities are based is given by fig. 9.5.

A comparison of various NDI method capabilities was published in [15] .

10. IMPACT OF NDI METHODS ON THE STRUCTURAL SAFETY APPROACHES

10.1. The role of NDI methods in the more recent requirements and applicable criteria

In the para 5., 6., 7., and 8., the main features of recent requirements and applicable criteria have been reported to give a basis for the discussion on the evolution of the structural design safety criteria and of the role of NDI methods involved.

Of course, the evolution emerging from such documents sometimes is faster than the real application, especially when the requirements indicate design criteria which are to be introduced in some technical milieus. Such evolution is sometimes slower, where, besides the indicated safety criteria, design methodologies and criteria have been developed, as for instance when it was necessary to give practical application to the fail-safe concept in its dawning.

In any case, though in the awareness of the differencies between practice and requirements, the analysis of the requirements themselves is clearly indicative of the evaluation of the NDI method impact.

The FAR 25, [11] , adopted since 1964, have been successively amended several times. As concerns structural safety, the amendment on "sonic fatigue evaluation" dated 1966, and the more recent amendments on "fail-safe strength", are important to our pourpose. NDI methods are not mentioned, and the same "fail--safe" design concept is applied on the basis of the hypothesis of the fatigue failure or obvious partial failure of a single principal element. The principle of periodical inspections and the damage tolerance is not present; moreover neither flaws or cracks are specified as initial inperfection to be taken into account.

Structural design criteria prepared for the application to a space shuttle, [12] , dated 1971 (revised 1972), take widely into account the need for new materials, whose data characterization must be made by the same hardware constructor. Among the material characteristics to be evaluated there are explicitly the material failure mechanisms. The document "is intended as a starting point for preparation of requirements and specifications for the space shuttle". The proof-test is introduced as "non-destructive test" and explicit mention is made of the other NDI methods, in particular with indications on the applicability in the factory and on the field of the various techniques, and with reference to various material types (refractory alloy , ceramics, composites). The development and the evaluation of techniques for inspection are requested. In particular, as concerns safe crack-growth life design concept, it is requested "to demontrate that non-destructive inspection techniques are adequate". The standards of such NDI methods are the basis for analysis of the flaw-grow because they give "the maximum permissible initial flaw size" to be considered.

When the safe-life concepts depend on the proof-test, the avoidance or the reduction of proof-test failures is to be obtained by determining the required NDI "amount and type". The principle of periodic inspection is introduced and the inspection period is the base for the definition of the requirements on fatigue life in the fail-safe concept and on crack-growth in the safe crack-growth life concept. The great impact of NDI procedures emerges from the statement that the allowable size of flaws or defects shall be large enough to be detected by practical inspection procedures", and constitute a condition for the adequacy of the design.

The MIL-A-83444, Airplane damage tolerance requirements, [13] , dated 1974, represent a strong introduction into the structural safety field of the fracture mechanics analysis and of the periodical inspections principle. They also denote a great confidence into the NDI method capabilities, giving precise indications on the flaws which are to be assumed to exist after factory and in-service inspections. The entire body of requirements is based on "the inspection of 100 percent of all fracture critical regions of all structural components". Flaw sizes lower than the specified sizes may be assumed if "special non-destructive inspection procedures have demonstrated a detection capability better than indicated" by the flaw size specifications. The values to be adopted must have at least 90 percent probability to be detected with a 95 percent confidence level. These values must be obtained in a"non-destructive testing demonstration program" "performed by the contractor and approved by the procuring activity".

10.2 Actual use of statistical properties in the structure design safety approaches.

The present trend of safety in the aerospace structures seems to be the effort of finding reliable correlations between statistical properties of the various quantities involved, in order to give deterministic criteria based upon probabilistic analysis. Such trend is a continuation, at a more sophisticated level of the technology and with the necessary adaptations, of the well known approach of the static load structural safety, where a deterministic safety factor is imposed between two statistical properties i.e., the loads which are probabilistically exceeded only a fixed number of time in a given period, and the strength which is probabilistically exceeded by a given percent of nominally identical structures.

The characterizing aspect of the more recent safety philosophy is the introduction of the inspection intervals, not only as the fail-safe concept is concerned, but also in the new "slow crack-growth structure". The inspection interval to be adopted depends on the type ofinspection considered; but it is difficult to say whether the various proposed interval times depend more on deterministic rather than probabilistic considerations. In any case, such interval times weakly influence the safety levels because of the nature of the requirements which refer to statistical properties of the loads and the strengths during the same

intervals and to statistical properties of the structures as delivered by the inspections.

An important element for the safety approach in the fracture mechanics is the assumption on the presence of flaws or cracks after the construction or an inspection. It is assumed that there are present flaws or cracks which have a given probability to be not detected with a given confidence level, taking also into account the influence of the operator. This implies experimental analysis of the capabilities of the various NDI methods and the evaluation of the quality of the operator, but results in probabilistic property assumed as a starting point for the analysis.

Besides the initial inspections the requirements are based on two kinds of elements. One of them regards the periods of time on which to evaluate the damage propagation of cracks caused by the application of the proper load conditions. The other regards the loads that must be withstood after the damage previously said

The periods are defined as multiples of the inspection intervals by means of deterministic multiplication factor.

The loads to be withstood are defined statistically as the loads which have a given probability to be exceeded in given periods of time. In this definition other periods intervene, different from the previous ones, but deterministically defined as multiples of the inspection intervals.

An analysis of the requirements themselves and their basic elements indicates, that they suppose the possibility to reach (deterministic) statements on the basis of statistical information . As a sample, we can consider the requirements on residual strengths for a multiload path fail safe structure with a depot or base level inspection. The remaining structure, subsequent to load path failure, must not fail (aircraft failure) under a given load when its cracks propagated under the action of the actual loads in a given period.

Such an approach implicates the possibility of finding simple conditions between statistical phenomena. In particular are to be studied the crack start and the crack propagation under random loads. It is well known the difficult to foresee the fatigue behaviour under random loads on the basis of cyclic test. 'Ad hoc' random test seem to be necessary.

As a sample of statistical properties, to be obtained from statistical description of a phenomenon, we can consider the case of the gust loads.

The data on atmospheric turbulence are given by means of the two functions below.

1) Probability density f , as function of root mean square gust velocity σ_u ,

$$f = f(\sigma_u) \ ,$$

or as cumulative probability F , as function of σ_u , at various altitude ,

$$F = F(\sigma_u) .$$

2) Power spectral density $\Phi(\Omega)$ of the gust velocity, as function of σ_u and of the reduced frequency $\Omega = \frac{2\pi}{\lambda}$ (λ being the wave length). As a sample (for a wide insight into the topic, see [10]):

$$\Phi(\Omega) = \sigma_u^2 \, \frac{L}{\pi} \cdot \frac{1+3\,\Omega^2 L^2}{\left(1+\Omega^2 L^2\right)^2} \ ,$$

where L = 1000 ft is an acceptable value.

These functions give a probabilistic description of the turbulence that shall be encountered in flight. Their current use is based on the determination of the gust velocity power spectral density $p(\omega)$, where ω is the frequency, taking into account the airspeed, and on the calculation of the power spectral density $p(\omega)$ of every quantity α can be necessary to know, as dynamic response of the airplane to the gust input (1).

An asymtotic (for large y) approximate relation between the everage number $N(y)$ of maximum per second exceeding a given positive value y and the power spectrum $p(\omega)$ of a stationary Gaussian disturbance, having root mean square σ, is :

$$N(y) = \frac{1}{2\pi} \left[\frac{\int_0^\infty \omega^2 \, p(\omega) \, d\omega}{\int_0^\infty p(\omega) \, d\omega} \right]^{\frac{1}{2}} e^{-\frac{y^2}{2\sigma^2}} \ , \qquad (y > 0) \, .$$

If applied also to the α's quantities, when there is not the certainty that they are Gaussian (instead the input u is Gaussian), it allows us to obtain an approximate value of the expected cumulative distribution of positive maxima exceeding a fixed positive value y and of negative minima exceeding in modulus a negative fixed value y .

(1) See for instance [10] .

Taking into account the continuous variations in the root-mean square gust velocity, the cumulative distribution of maximum per second exceeding a given positive value y is

$$M(y)= \frac{1}{2\pi}\left[\frac{\int_0^{\infty}\omega^2\, p(\omega)\; d\omega}{\int_0^{\infty} p(\omega)\; d\omega}\right]^{\frac{1}{2}} \int_0^{\infty} f(\sigma)\; e^{-\frac{y^2}{2\sigma}}\, d\sigma$$

The same expression is valid also for the cumulative distribution of minimum per second exceeding in modulus a given negative value.

Such expression is the basis for the evaluation, for instance, of the medium number of loading conditions exceeding a given value during an interval of flight time, or the loading condition that can be expected to be exceeded a given number of times in a given interval (for instance between two inspections).

For a discussion of the reliability of the above expression see [12].

Expression have been evaluated also to obtain approximate evaluations of the fatigue loading conditions. As it is known, fatigue loading is made by cyclic variation of load. The passage from a maximum (minimum) to a minimum (maximum) is an half cyclic variation.

For instance, according to Kowalewski (see [19]), the joint density function of m and a,

$$H(m,a)= \frac{N_1}{\sqrt{2\pi\ \sigma^2(1-I^2)}}\, e^{-\frac{m^2}{2\sigma^2(1-I)^2}}\ \frac{a}{\sigma^2\ I^2}\ e^{-\frac{a^2}{2\sigma^2 I^2}},$$

where m is the mean, a is the amplitude of a certain Gaussian process, and where

N_1 is the number of peak (the number of troughs),

I is the irregularity factor (See [19]), $I=\frac{N_1}{\bar{N}}$,

$\bar{N}$ is the zero level crossing with positive slope,

allows us to calculate the environment due to a stationary Gaussian process having a root mean square.

The determination of the power spectral density of load or of a quantity such as the load on an element or the stress at a point — directly connected with the fatigue damage or the requested residual strength, on the basis of the power spectral density of an input such as gusts, thrust instability and so on, is a dynamic response problem.

The classical approach to this problem is the use of the Laplace transform and the determination of the transfer function and in particular of the frequency response which allows us to determinate the response power spectrum.

Recently the dynamic response problem in the case of sonic fatigue, where several hundreds of characteristic modes are involved, have been approached by means of the Statistical Energy Analysis (S.E.A.).

11. CONCLUDING REMARKS

NDI methods are basic tools in a modern approach of the structure safety achievement. They allow the designer to know reliable starting points for the fracture mechanics analysis and the production and inspection specialist to detect flaws and cracks in order to evaluate each structure component.

New methods for NDI will be proposed and tested in the future. Among them for instance the emission of electrons by the surface fractured zones activated by ultraviolet rays, is an effect now under consideration at scientific laboratory level.

The knowledge of the various NDI method capabilities is a stochastic problem that introduces new probabilistic aspects into the safety approaches.

In any case, fracture mechanics and NDI methods are coupled between them in the new area of the damage tolerance structure.

In the future it will be necessary to improve the knowledge of the NDI method capabilities, and on the other hand to search for further theoretical and experimental results on the various material behaviour as concerns crack propagation under random loads.

The arguments discussed in this paper need the consciousness of their difficulty and delicacy. My statements shall be considered as personal judgment, whose only purpose is to promote a general view of the problem without any wanted criticism of eventual different points of view. In any case, the trend of the technological progress seems to be the full acquisition of fracture mechanics and random loads into the structural safety approach, where NDI methods shall have a role of increasing importance.

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TAB.III-1 - TYPICAL STATISTICAL DISPERSIONS (from [6])

	Coefficient of variation (practical)	Materials	Structures
Steel	Fracture strength	7-10%	
	Yield stress	5 - 7%	7-10%

TAB. 7.I - P_{XX} LOADS FOR VARIOUS DEGREES OF INSPECTABILITY, P_{yy} LOADS (From [13])

P_{XX}*	Degree of Inspectability	Typical Inspection Interval	Magnification Factor, M
P_{FE}	In-Flight Evident	One Flight	100
P_{GE}	Ground Evident	One Flight	100
P_{WV}	Walk-Around Visual	Ten Flights	100
P_{SV}	Special Visual	One Year	50
P_{DM}	Depot or Base Level	1/4 Lifetime	20
P_{LT}	Non-Inspectable	One Lifetime	20

* P_{XX} = Maximum average internal member load that will occur once in M times the inspection interval. Where P_{DM} or P_{LT} is determined to be less than the design limit load, the design limit load shall be the required residual strength load level. P_{XX} need not be greater than 1.2 times the maximum load in one lifetime, if greater than design limit load.

The loads P_{xx}, where xx assumes proper value for each degree of inspectability, are the base for the requirements of the slow crack-growth structure and for the fail-safe structure which remains after a load path failure (or crack arrest). The load P_{yy} is a minimum load that fail-safe structure must sustain at the instant of load path failure (or crack arrest). P_{yy} shall include a dynamic factor (D.F.) and "should be equal to the internal member load and design limit load or (D.F.) P_{xx} whichever is greater". In the lack of data a D.F. of 1.15 is suggested.

TAB.7-II - SLOW-CRACK GROWTH STRUCTURE (derived from [13]).

Inspectability	Residual strength req.and damage growth limitsfor intact structure
In-flight evident	Non-applicable
Ground evident	Non-applicable
Walkaround visual	Non-applicable
Special visual	Non-applicable
Depot or base level	Damage size shall not grow to critical size and shall not cause failure, due to the application of P_{DM}, in a period two times the inspection interval.
In service non-inspectable	Damage size shall not grow to critical size and shall not cause failure due to the application of P_{LT} in a period two times the design lifetime.

TAB. 7.III - FAIL-SAFE MULTIPLE LOAD PATH STRUCTURE, [13]

Inspectability	Residual strength req.and damage growth limits for intact structure	Residual strength req.and damage growth limits for remaining structures subsequent to load path failure
In-flight evident	o If structure is depot or base level inspectable for less than failed load path (e.g. subcritical flaws):	o Must sustain P_{yy} at time of load path failure o 1 shall not cause aircraft failure $\mathcal{C}P_{FE}$ during return to base.
Ground evident	a_d shall not grow critical $\mathcal{C}P_{DM}$ in one depot or base level inspection interval or	o Must sustain P_{yy} at time of failure o 1 shall not cause aircraft failure $\mathcal{C}P_{GE}$ in one flight
Walkaround visual	o If structure is not depot or base level inspectable for less than failed load path:	o Must sustain P_{yy} at time of failure o 1 shall not cause aircraft failure $\mathcal{C}P_{WV}$ in 5 times the inspection interval
Special visual	a_i shall not grow to critical $\mathcal{C}$ P_{LT} in one lifetime	o Must sustain P_{yy} at time of failure o 1 shall not cause aircraft failure $\mathcal{C}P_{SV}$ in 2 times the inspection interval
Depot or base level		o Must sustain P_{yy} at time of failure o 1 shall not cause aircraft failure $\mathcal{C}P_{DM}$ in 2 times the inspection interval

a_d = "assumed depot or base level damage sizes"

a_i = "assumed initial flaw sizes"

1 = "failed load path plus assumed damage in remaining structure"

$\mathcal{C}$ = "due to the application of . . . "

TAB. 7.IV - FAIL-SAFE CRACK ARREST STRUCTURE, [13]

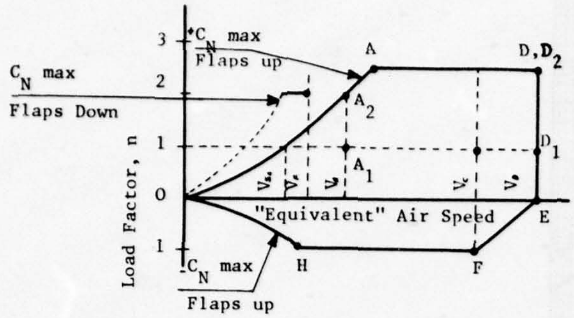
Inspectability	Residual strength req.and damage growth limits for intact structure	Residual strength req.and damage growth limits for remaining structure subsequent to unstable growth and arrest
In-flight evident	o If structure is depot or base level inspectable for less than arrested damage(e.g.subcritical flaws):	o Must sustain P_{yy} at time of unstable cracking o 1'shall not cause A/C failure $\mathcal{C}P_{FE}$ during return to base
Ground evident	a_d shall not grow to critical $\mathcal{C}$ P_{DM} in one or base level inspection interval	o Must sustain P_{yy} at times of unstable cracking o 1'shall not cause A/C failure $\mathcal{C}P_{GE}$ in one flight
Walkaround visual	or	o Must sustain P_{yy} at time of unstable cracking o 1'shall not cause A/C failure $\mathcal{C}P_{WV}$ in 5 times the inspection interval
Special visual	o If structure is not depot or base level inspectable for less than arrested damage:	o Must sustain P_{yy} at time of unstable cracking o 1'shall not cause A/C failure $\mathcal{C}P_{SV}$ in 2 times inspection interval
Depot or base level	a_i shall not grow to critical $\mathcal{C}$ P_{LT} in one lifetime	o Must sustain P_{yy} at time of unstable cracking o 1'shall not cause A/C failure $\mathcal{C}P_{DM}$ in 2 times inspection interval

a_d = "assumed depot or base level damage sizes"

a_i = "assumed initial flaw sizes"

1' = "damage depending on geometry" (see [13])

$\mathcal{C}$ = "due to the application of . . . "

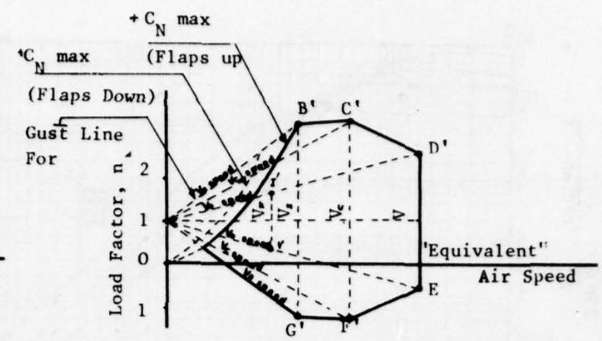


"Equivalent" Air Speed
Load Factor
Flaps Up
Flaps Down

n = Center of Gravity Acceleration due to Aerodynamic Lift

$$\begin{cases} n_{max} \geq \left(2{,}1 + \left(\dfrac{24.000}{W+10.000}\right)\right) \quad W = \text{max take-off weight} \\ 2{,}5 \leq n_{max} \leq 3{,}8 \\ n_{min} \leq -1 \end{cases}$$

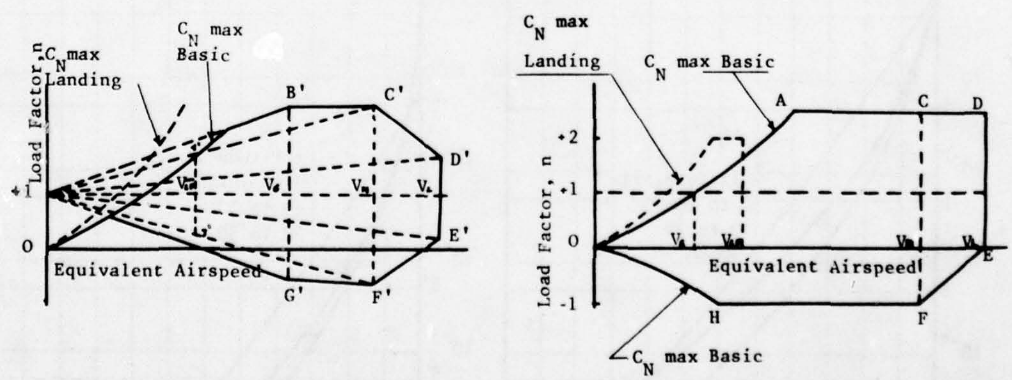
Fig.3.1 - FAR 25 Manoeuvre Diagram,[11]



Speed
Gust Line

AIRSPEED	ALTITUDE	V_{de}
V_B	0 ÷ 6000 m	± 20 m/s
V_B	6000÷15000 m	± 20÷11,4 m/s
V_C	0 ÷ 6000 m	± 15 m/s
V_C	6000÷15000 m	± 7,6 m/s
V_D	0 ÷ 6000 m	± 7,5 m/s
V_D	6000÷15000 m	± 3,75 m/s

Fig.3.2 - FAR 25 Gust Diagram,[11] .



a) - Symmetrical Gust Envelope (from [12] - b) - Symmetrical Manoeuvre Envelope (from [12])

Fig.3.3 - Manoeuvre and Gust Diagrams valid for Space Shuttle.

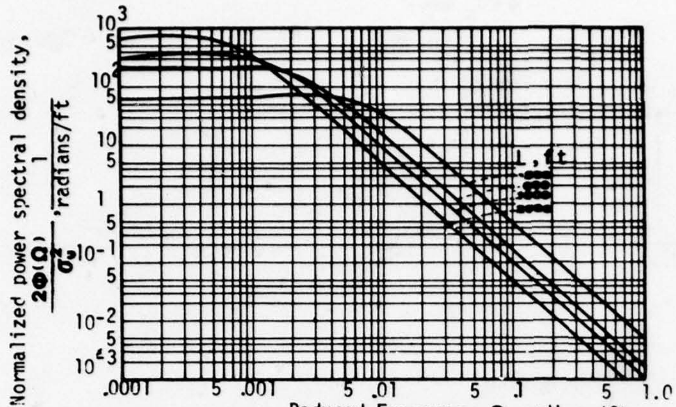


Fig.4.1-Analytic representation of the spectrum of atmospheric turbulence, [7].

$$\Phi(\Omega) = \sigma_u^2 \frac{L(1+3\Omega^2 L^2)}{2\pi(1+\Omega^2 L^2)^2}$$

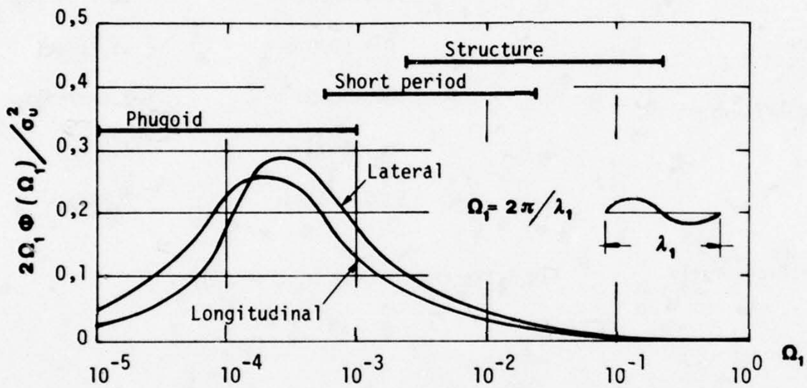


Fig.4.2 - One dimensional spectra, isotropic turbulence, scale L = 5000 ft., [10].

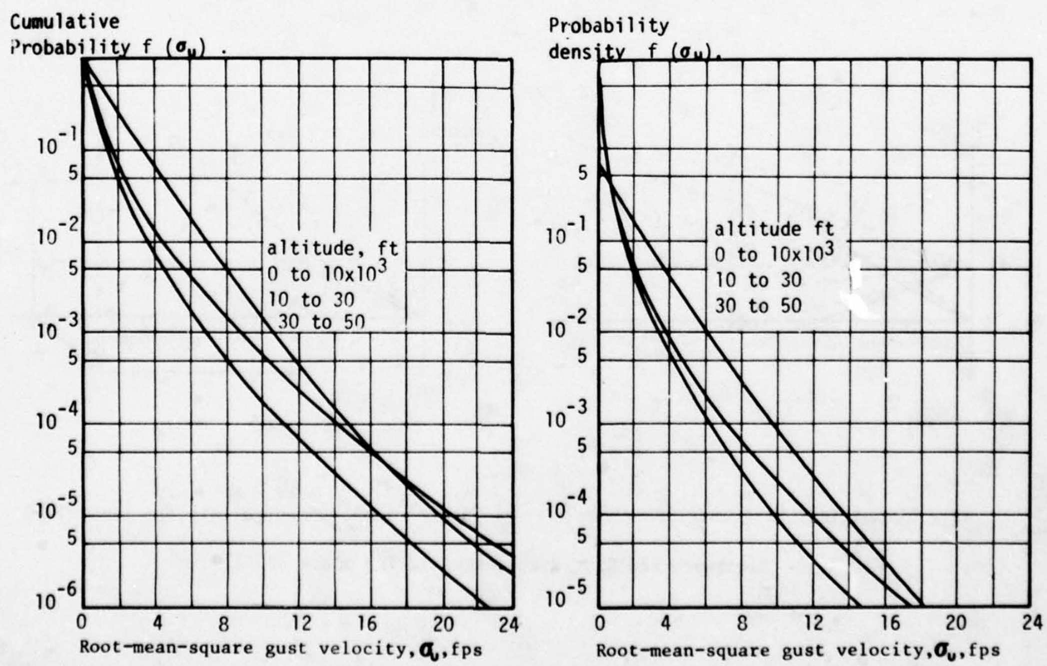


Fig. 4.3- Cumulative Probability Density of Gusts of given Roof-Mean Square Velocity to be encountered in Fligth, [7].

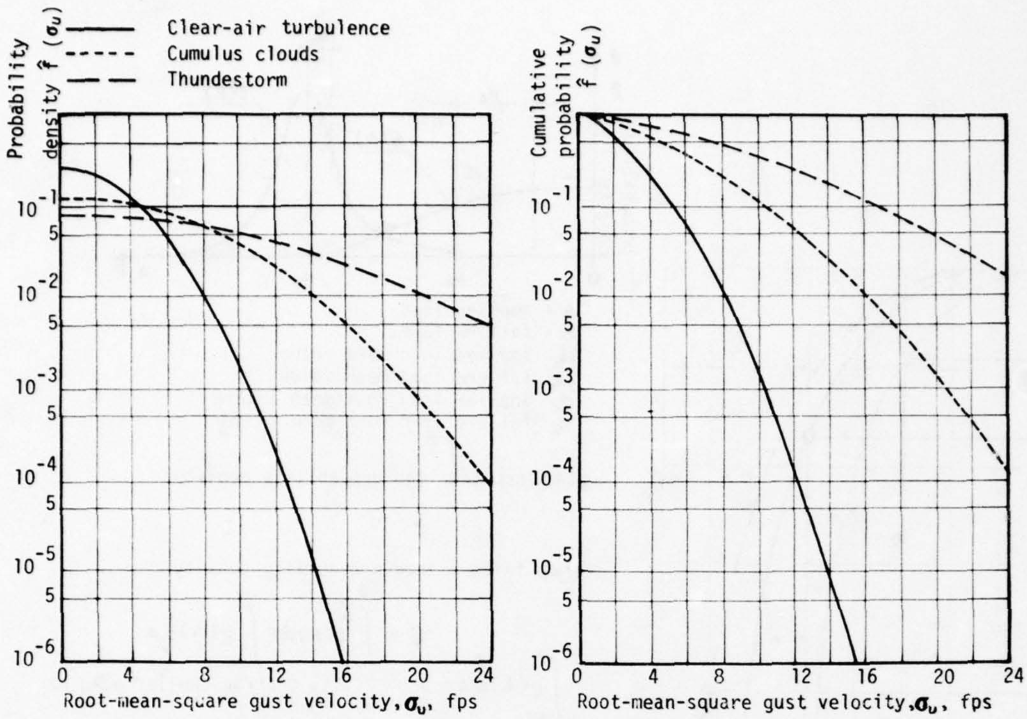


Fig.4.4 - Cumulative Probability and Probability Density of Gusts of given Root-mean-square Velocity to be encountered in Turbulence,[7].

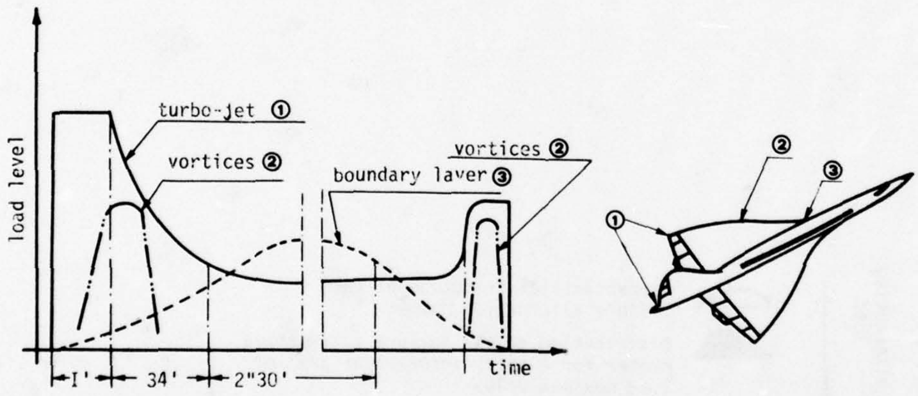


Fig.4.5. - Sources of acoustic noise, reported from J.Gay, AGARD CP-113, [21] .

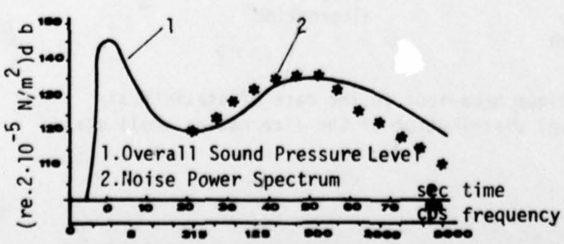


Fig.4.6-Acoustic Environment in the Cargo Bay of Space Shuttle,[8].

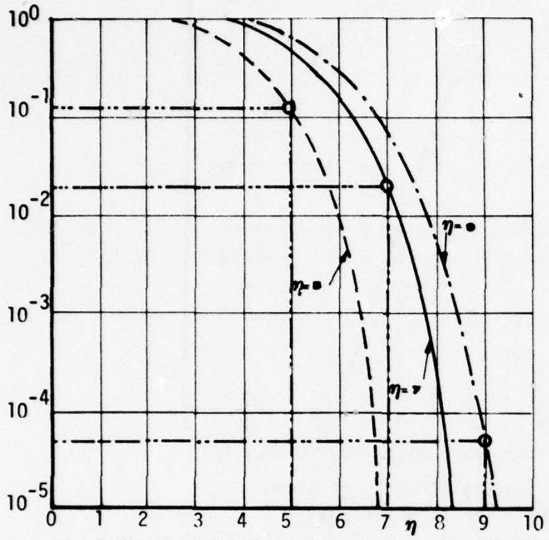
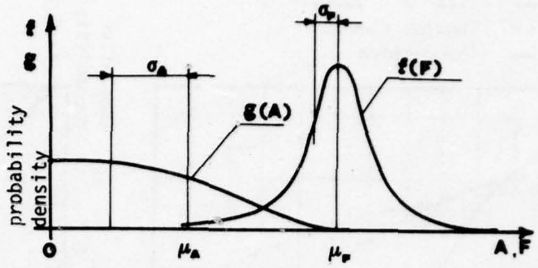


Fig.4.7 - Probability of exceeding load factor η in 'X' hours, from [9].



A = applied load
F = failure load
μ_A = applied load mean value
μ_F = failure load mean value
σ_A = applied load root mean square
σ_F = failure load root mean square

g(A) = applied load probability density

f(F) = failure load probability density

$$S = \int_{-\infty}^{\infty} f(F)dF \int_{-\infty}^{F} g(A)dA$$

$\int_{-\infty}^{F} g(A)dA$ = probability that an applied load may be lower than F

$f(F)\,dF$ = probability that a failure load may be in the interval d F.

Fig.4.8- Probabilistic Interpretation of the deterministic Factor of Safety

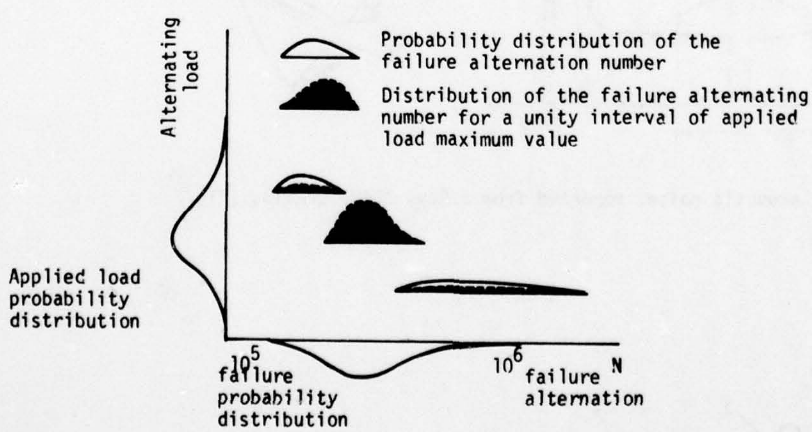


Fig.4.9-Fatigue behaviour in the case of statistical (qualitative) distribution of the alternating amplitude.

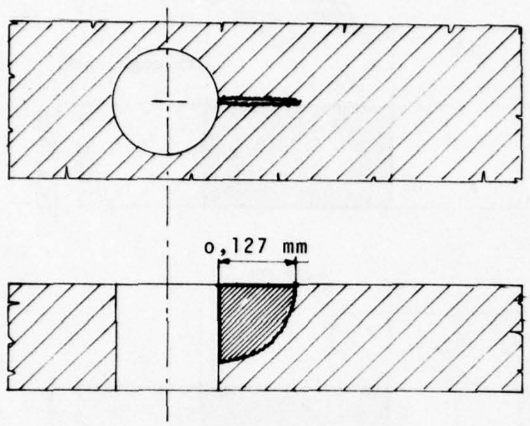


Fig.8.1 - Small imperfections assumptions.

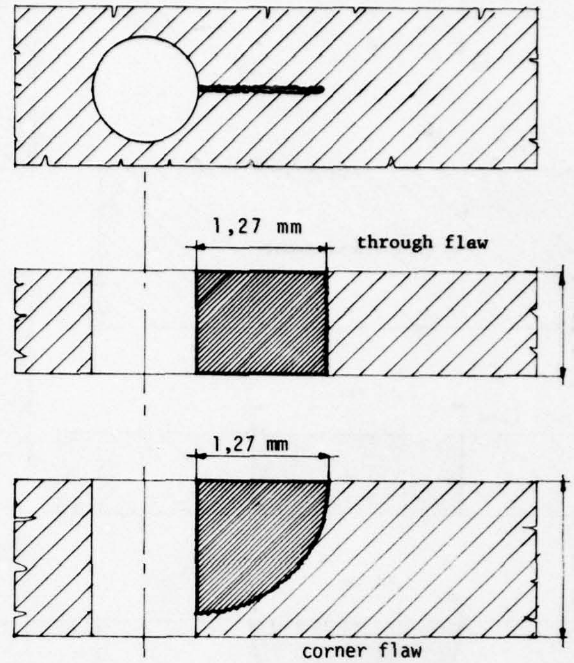


Fig.8.2 - Slow crack growth structure flaw assumption. Location at holes and cutouts.

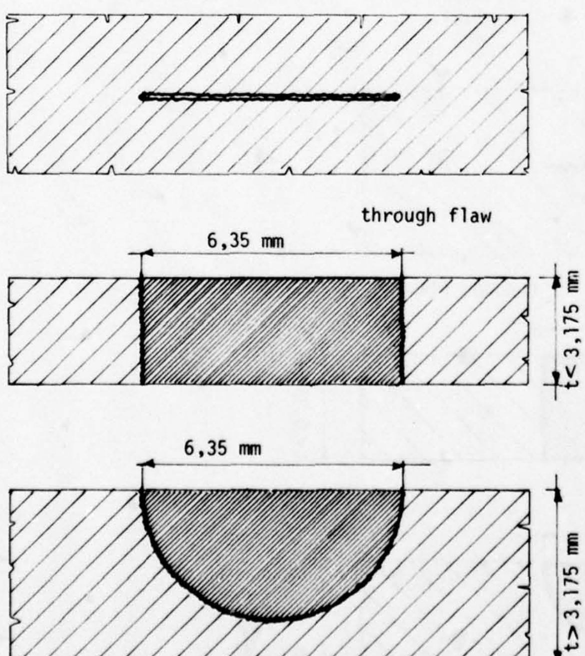


Fig. 8.3 - Slow crack growth structure flaw assumption. Location other than holes and cutouts.

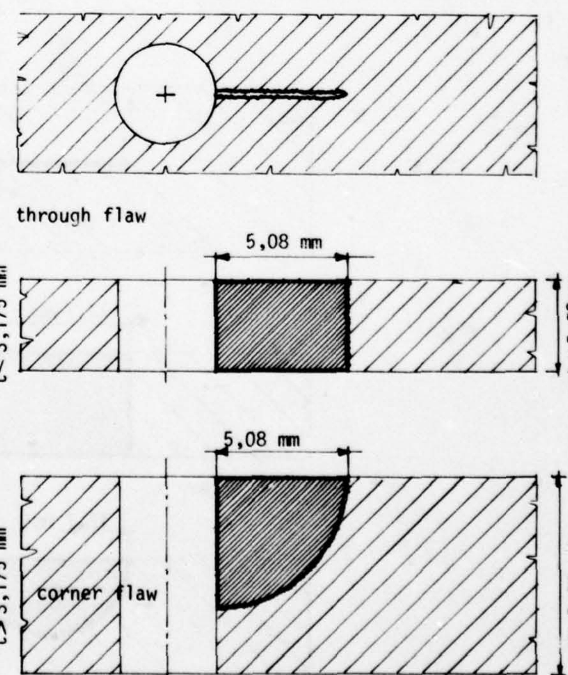


Fig. 8.4 - Fail safe structure flaw assumptions. Location at holes and cutouts.

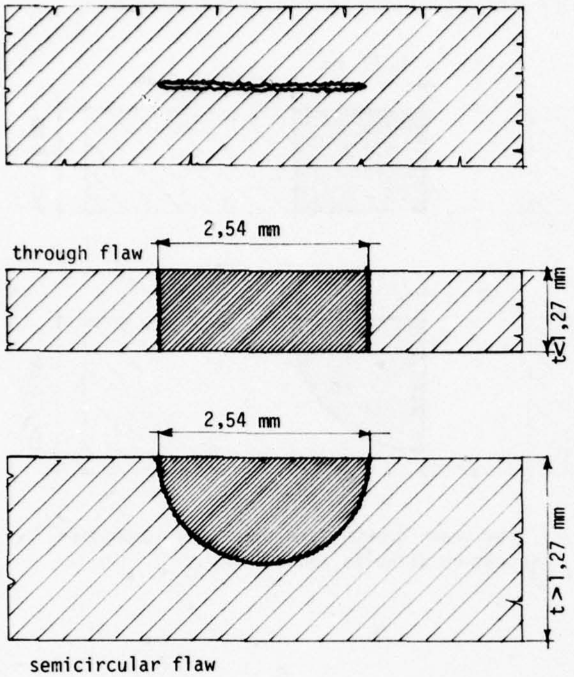


Fig.8.5 - Fail safe structure flaw assumptions. Location other than holes.

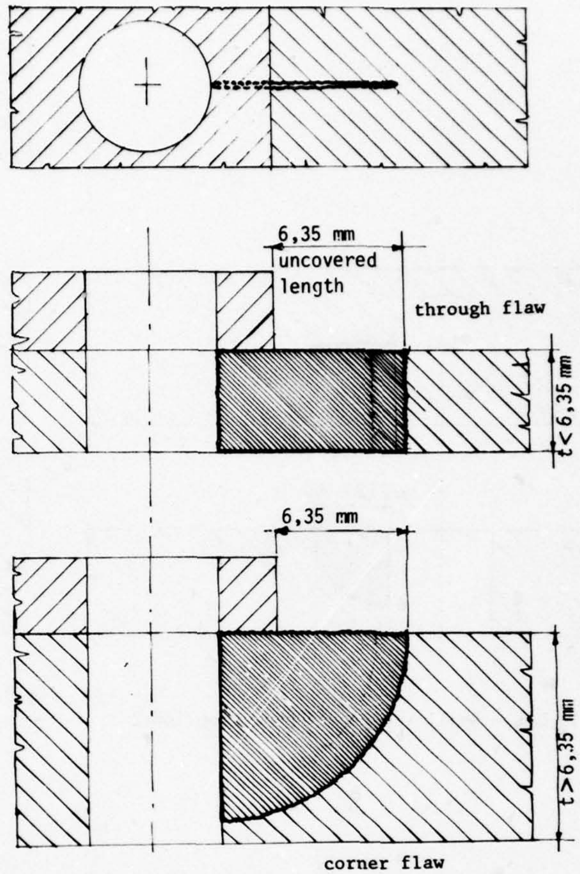


Fig. 8.6 - In service inspection flaw assumptions. Location at holes and cutouts without removal.

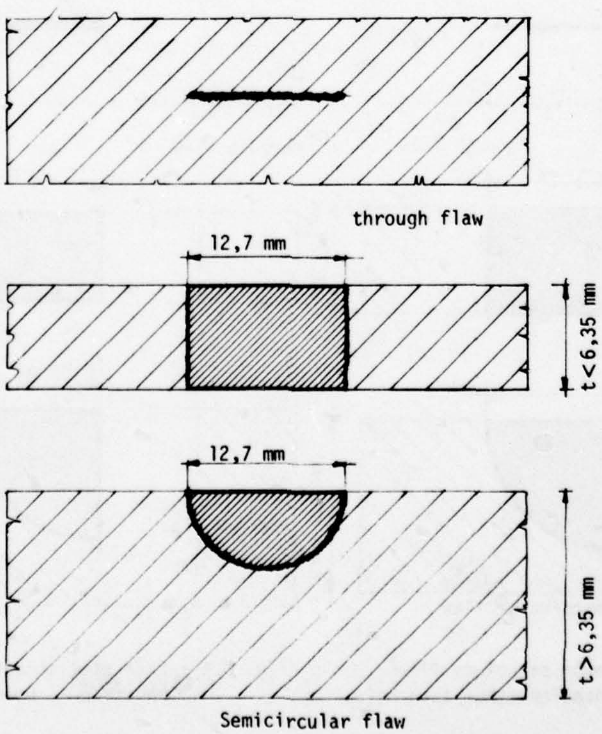


Fig. 8.7 - In service inspection flaw assumptions.

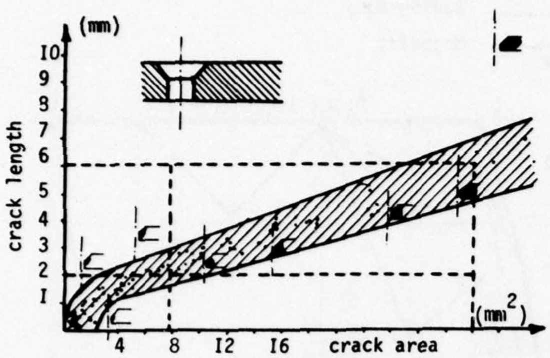


Fig.9.1-Connection between crack area and crack length as an aid for valueing ultrasonic indication from carousel method,from Ekkart Knorr in [18].

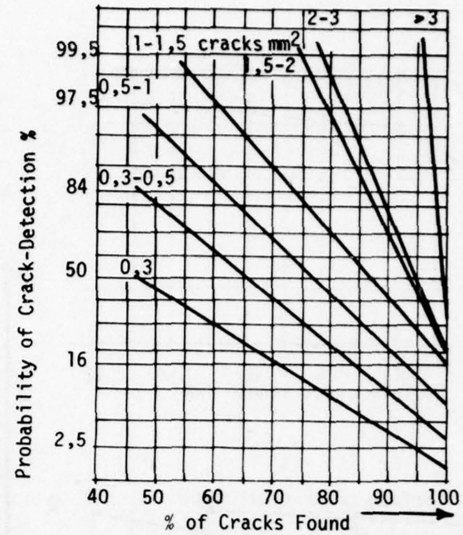


Fig.9.2a - Mean Probability of Crack Detection using Manual Eddy Current Method,dependent from Crack Areas,from Ekkart Knorr in [18].

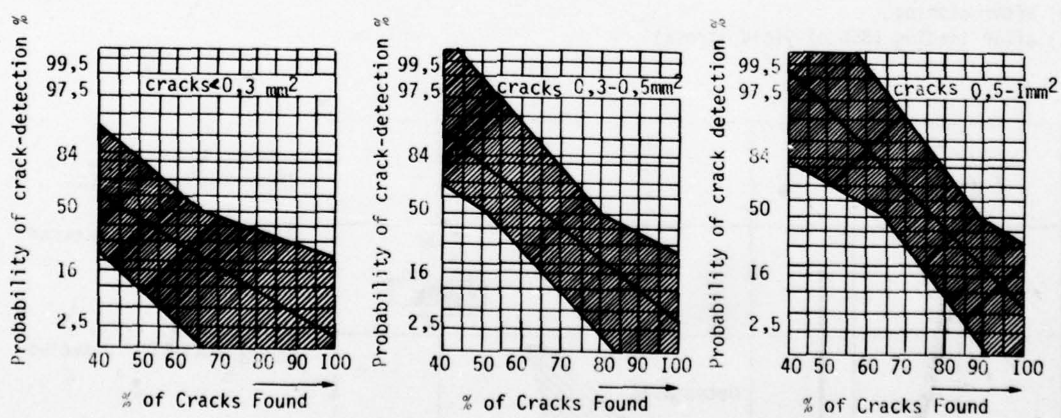


Fig.9.2.b - Mean probability and zone of confidence for different classes of crack areas by eddy current, from Ekkart Knorr in [18]:

a) all cracks up to 0,3 mm²,

b) crack areas 0,3 and 0,5 mm²,

c) crack areas 0,5-1 mm2.

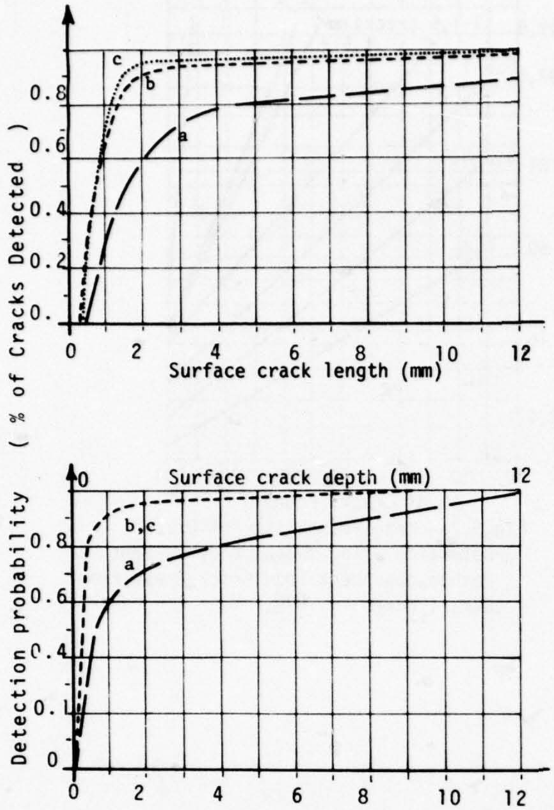


Fig.9.3-Fluorescent l.p. detection sensitivity at 95%,probability and 95% of confidence level for flat fatigue cracked specimens of 2219-T87 aluminium alloy,fromW.D.Rummel et Al.as quoted in [15]. Surface conditions:

a) as machined,
b) after etching,
c) after loading (85% of yield stress).

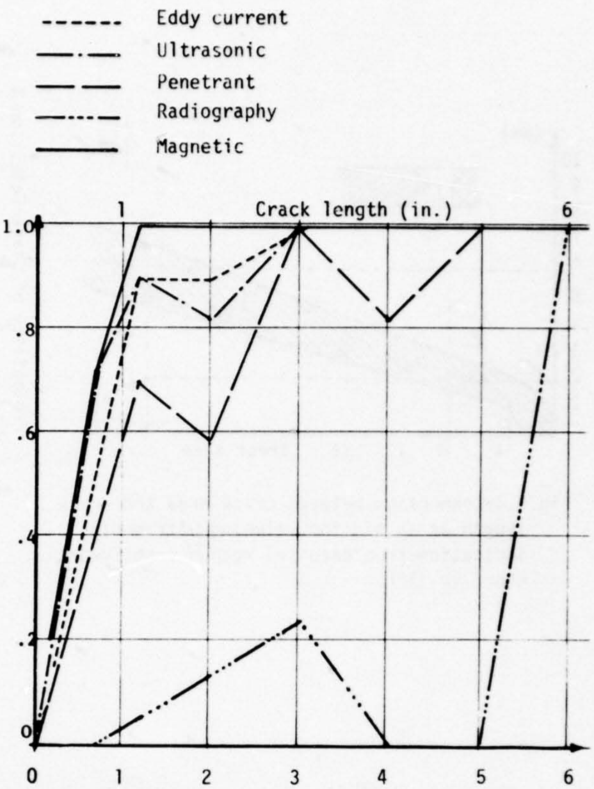


Fig.9.4-Sensitivity of the five NDI Methods to Surface Flaws in Program Specimens, from H.Southworth as quoted in [17].

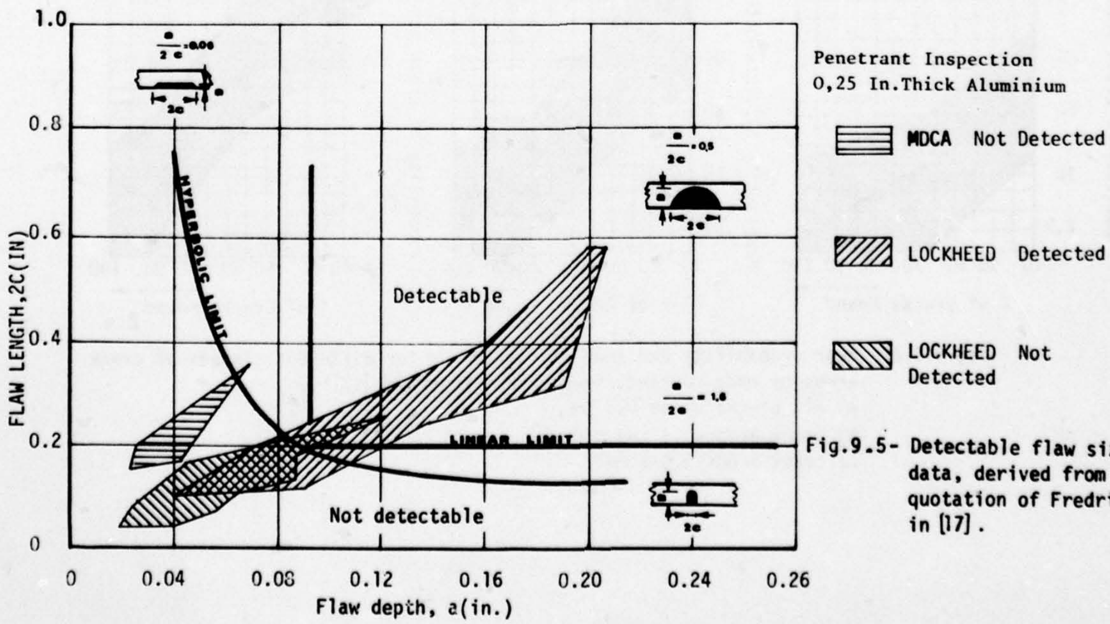


Fig.9.5- Detectable flaw size data, derived from quotation of Fredric in [17].

THE ECONOMIC IMPLICATIONS OF NDE: OPPORTUNITIES AND PAYOFF

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SUMMARY

In the past, the development of nondestructive evaluation (NDE) for aircraft applications has responded primarily to the need to assure structural integrity and mission reliability. The cost of inspection and the economic return on investment were considered secondary issues. The situation is now changing. NDE is experiencing increased growth and in many cases, opportunities for direct economic payoff are providing considerable motivation.

Recent progress in the development of NDE procedures and instruments which may have significant economic benefits is reviewed. NDE requirements in both initial manufacturing and in-service functions are discussed to exemplify cost-effective approaches. Other possible future opportunities are also considered.

INTRODUCTION

The importance of nondestructive evaluation (NDE) in the manufacture and service use of aircraft systems is becoming well established and considerable technical progress has been made in the last several years to advance the state-of-the-art. This importance will continue to grow as more occasions are encountered in which the capability of the NDE function may be the controlling factor in meeting some aircraft design, performance and operational cost objectives.

Historically, the development of NDE techniques for aircraft applications has concentrated on providing inspection capabilities to help assure structural integrity for flight safety and mission performance reliability as overriding issues. To that end, emphasis during initial manufacturing has been focused on applying NDE to assure that only parts free of critical defects will be accepted, while in service it has been focused on NDE for the timely detection of mission-limiting failure conditions. While the cost of performing NDE and the cost of technological development is always of concern, the assurance of flight safety and operational reliability, whatever the cost, has been the prevailing requirement. Having first satisfied this requirement, any economic benefit gained from an NDE function could be considered an added payoff. Due to this emphasis, there has been much less pressure, and therefore less motivation and opportunity to exploit NDE as a means to reduce costs directly.

This situation is changing rapidly, however. As a natural consequence of the greater initial cost of new advanced aircraft having increased sophistication, the rising cost of replacement aircraft, and as the costs of maintenance operations escalate, the total cost of aircraft ownership is growing significantly. Figure 1 compares the relative life cycle costs for several aeronautical and one electronic system based on a 15 year service life. The life cycle cost includes system research and development, initial acquisition price and the cost of operation and support (O&S) during system life. Operation costs include crew and consumable expenses. Support costs include inspection and maintenance parts and labor. A high usage-rate manned aircraft, such as a bomber or transport, characteristically involves significantly higher total costs. Furthermore, the O&S costs usually constitute the major portion of the life cycle costs as shown.

The reduction and control of the increasing life cycle cost trend, without sacrificing mission readiness, has become an additional critical objective in the United States Air Force (USAF). Cost reduction opportunities are being sought in both the acquisition and O&S phases of existing systems and those in development. Experience is showing that through the use of emerging technology improvements, NDE offers tremendous economic potential in many applications. As the role of NDE continues to expand, economic considerations are becoming more important.

Some of the more significant factors involved in this expansion, as discussed in detail in Reference 1, are: (1) the pressure to minimize O&S costs (as previously discussed), particularly through life extension and early damage detection, (2) the application of damage tolerant design requirements to new aircraft systems and (3) the emergence of new structural concepts, processes and materials. Certain of these factors will result in direct economic advantages, while others may increase the actual cost of inspection, but by so doing, result in significant total cost savings indirectly.

For example, the introduction of damage tolerant design requirements for certain fracture/fatigue critical parts to insure that the probability of detecting flaws above a given size is very high may increase the actual cost of manufacturing inspection. These increased costs can result from the requirement for more critical inspection operations, including the necessity of demonstrating the manufacturer's capability to detect flaws on a statistically reliable basis at a 90% probability 95% confidence level. On the other hand, assurance of the reliability of these critical components over the design life-time of the aircraft can greatly minimize the maintenance costs associated with that system.

New structural concepts, processes and materials can also increase the direct inspection costs of components. The introduction of near-net shape forged components, for example, can increse the complexity of the inspection problem. In this case, however, the total manufacturing cost even with increased inspection costs can be significantly lower. This will be discussed later.

Accepting the fact that several of these factors expanding the role of NDE can result in increased manufacturing inspection costs per se, it is interesting to consider the effect that such increases may have on the total costs of aerospace hardware.

A U. S. National Materials Advisory Board Panel is currently assessing the major cost factors associated with the inspection process in the aerospace industry for the U. S. Department of Defense (Ref 2). Figure 2, which cites the results of an earlier Aerospace Industries Association Report augmented by an industry survey of the costs of inspection of both engine and airframe forgings, shows that the total cost of inspection is a relatively small percentage of the total sales price of the component or system. Therefore, the impact on the total selling price of the system caused by increasing the inspection cost is minimal.

On the other hand, an example illustrating that direct costs can be reduced if reliable NDE is available is shown in Figure 3 in the case of advanced composites (Ref 3). If the inspection technology is not considered adequate to guarantee the integrity of advanced composite components, it will probably be necessary to proof-test each individual component to satisfy the requirements of U. S. Mil Std 1530 "Aircraft Structural Integrity Program." The economic implications of such a requirement are illustrated where the minimum cost for proof-testing empennage components is shown to be 2.75 to 3.75 times more expensive than the cost of applying conventional NDE methods to those parts. The addition of acoustic emission monitoring of the proof rest to insure that total failure of a part will not occur, thereby rendering it non-repairable, further increases this differential.

A detailed, quantitative assessment of the economics associated with the application of NDE to systems in both the manufacturing and operational environment is an extremely complex, difficult task and is beyond the objective of this paper. Rather, it is the intention here to discuss selected topics where NDE is a major consideration and illustrate, through analysis of these examples, that the economic implications of NDE are great indeed and that significant opportunities exist to exploit current and potential improvements in this technology. The balance of the discussion then, will include some current and near term opportunities both for manufacturing and in-service inspection and then speculate on the economic potential of technology currently in development.

CURRENT AND NEAR TERM OPPORTUNITIES

Manufacturing NDE

Much of the cost of the fabrication of high performance components for engines and airframes made of titanium and nickel base superalloys is in the machining of these components. For example, it is not unusual for 90% of the weight of a superalloy turbine disk forging to end up as machined chips. Not only is this expensive in terms of material loss, but also in terms of the difficulty in machining these alloys. This has been identified as the major cost driver in manufacturing parts of this nature (Ref 4). Consequently, considerable effort is underway to develop and use more efficient manufacturing methods to produce these parts in near net or even net shapes to drastically reduce the expensive processing operations required. The advantages of this technology are shown in Figure 4. Approaches being successfully pursued include powder metallurgy compaction, hot isostatic pressing and isothermal forging, separately or in combination, of titanium and nickel base alloys.

As these goals are achieved, the problem of economically inspecting the resultant components becomes much more difficult. For example no longer will it be possible to machine to an intermediate sonic shape with flat parallel surfaces to better accommodate ultrasonic inspection. No longer will it be possible to avoid inspection of the relatively thick, difficult-to-inspect surface layer normally machined away. The material very near the surface must now be inspected.

In anticipation of the development of this technology, it was recognized that to obtain the significant economic advantages that near net manufacturing offered, improved NDE was mandatory. General Dynamics/Fort Worth Division under Air Force Materials Laboratory (AFML) contract, has been developing a computer automated ultrasonic inspection system that holds promise for providing the inspection capability needed (Ref 5). This system uses a 5 axis bridge and an Automation Industries UM771 ultrasonic system which is controlled by a Digital Equipment Corporation PDP 11/45 digital computer with Tekronix Model 4010 memory scope, hard-copier and a special designed ultrasonic contour following subsystem that controls the orientation of the transducer, allowing it to automatically follow the contour of a complex forged shape. The basic system has been successfully demonstrated.

The contour following and computer control and display part of this system are now being incorporated by Pratt & Whitney Aircraft under AFML contract into a major computer controlled and operated unit that will be used for the inspection of near net turbine disks. The features of this system are listed as follows:

- Computer aided - - - - - - - - - - - - - -Automated system
- Contour sensing/following- - - - - - - -Inspect as-processed surfaces
- High sensitivity ultrasonics - - - - - -Resolve 1/64 FBH near surface
- Inspection record archives - - - - - - -Full, immediate data recall
- CAM dimension inspection - - - - - - - -Reduce machining set-up costs
- Defect analysis capability - - - - - - -Selective rejection criteria
- Statistical data analysis- - - - - - - -Fabrication process control

These disks are being manufactured by isothermally forging IN-100 nickel base superalloy powder metallurgy compacted and extruded billets. The system will have the capability to rapidly and automatically inspect near net shapes having an envelope of only 0.050 inch (1.27mm) as shown in Figure 5. It will be able to resolve indications equivalent to the reflection from a 1/64 inch (0.4mm) flat bottom hole at a depth of from 0.050 to 3 inches (1.27 - 76.2mm). This system will be operational in late 1977. It incorporates a pulser-receiver unit specially designed by TRW, Inc. that provides a high level of resolution (Ref 6).

In a parallel program the General Electric Company is building a similar system that differs in the contour-following approach in that it is a numerically-controlled system with electromagnetic sensors to provide the "fine-tuning", but which has the same basic objectives of computer controlled inspection of near net turbine disk shapes. Their pulser-receiver is a very high resolution system designed by the G. E. Research Laboratory in Schenectady, New York.

The capabilities of the computerized ultrasonic inspection system are being further exploited by General Dynamics as shown in Figure 6. To enhance system capabilities, parts transfer and manipulation, part edge following and multiple transducers have been added, with particular emphasis on application of the inspection of complex advanced composite components. A detailed study of cost reduction payoff was conducted which projected a savings of 77% in the inspection of these parts as compared to current state-of-the-art methods, based on a 1000 aircraft production buy (Ref 7).

All of these systems herald the introduction of computer control and interpretation in the ultrasonic inspection of critical parts in manufacturing operations. The economic implications are great indeed, for they reflect a willingness to make capital investments in equipment development that can lead to more rapid inspection made much more reliable by reducing dependence on the interpretative abilities of human inspectors. At the same time, total cost should be less by reducing the requirement for labor intensive tasks.

A less obvious, but nevertheless important and tedious inspection function receiving much greater attention is the measurement of dimensions and alignment. The proper alignment of aircraft fabrication and assembly tools is a critical requirement. To insure reproducibility, and thus provide quality assurance of assembled components, the conventional practice of maintaining and verifying tool alignment by periodic installation of a master gage as shown in Figure 7 has been adopted throughout the aircraft industry. In the conventional method, locators which are used to position parts during component buildup are initially positioned within the component tool superstructure by the master gage. Periodically the master gage is reinstalled to insure that these locators have not been misaligned. To accommodate these checks, the tool must be removed from production status for several shifts and significant labor costs are incurred to achieve the tool inspection. Current practice is to schedule inspections by the calendar rather than by a measured need. After this expenditure of time and effort, it is frequently found that no misalignment has occurred.

The use of analytical photogrammetry as an alternative method to detect and measure tool locator misalignment has been shown to offer major cost and precision benefits over conventional methods (Ref 8). This method provides indirect, non-contact measurements in real three-dimensional space through mathematical analysis of data extracted from multiple photographic images obtained from several camera positions. Thus, the decision for tool realignment is based only on the detection and measurement of locator displacements, rather than on a schedule. Photogrammetric measurements can be made on a non-interference basis during component fabrication and unnecessary master gage installation is avoided. Data collection and analysis involve considerably reduced labor costs and yield the required precision. Overall, the potential economic payoff is enormous. Production applications have been verified for relatively planar structural components such as wings and vertical fins by General Dynamics/Fort Worth Division. Follow-on development effort is getting underway shortly at G. D. under AFML sponsorship to extend this inspection and alignment method to more geometrically complex tools such as depicted in Figure 8 to broaden applications and economic payoff.

In-Service NDE

Improvements having significant economic impact can also be made in currently used field NDE methods. For example, the routine use of radiographic inspection throughout the USAF involves an enormous annual expense, just in X-ray film alone. Thus, an experimental direct exposure X-ray sensitive paper concept introduced in 1971 by Eastman Kodak was of considerable interest. USAF system evaluation (Ref 9) and field trials (Ref 10) have led to certified use. The paper system, which consists of a silver halide emulsion and development agent coating, can be developed right at the inspection site immediately after exposure in an inexpensive portable processor, in less than 15 seconds. The per sheet cost is approximately 21 cents compared to approximately $1.10 X-ray film cost. In addition, a trade-off study has shown a potential reduction of 60% in the manhours involved by using the more readily processed paper. The overall savings in time and material costs are quite substantial when one considers that almost 2000 radiographs may be taken of one C-5A transport during a major inspection. The system is now in field use.

One of the major problems facing the USAF is that of keeping many aircraft operational beyond their originally designed life span. As additional flying hours are accrued, there is increasing concern about the initiation and growth of fatigue cracks in the most highly stressed areas of the airframe structure. The most likely place for such flaws to initiate are adjacent to the more highly stressed fastener holes (Ref 11). A number of aircraft including certain models of the B-52 and KC-135 are already having skin and structure replaced in many areas to extend their life. In addition to problems with such "elderly" aircraft, the problem of the inadequate estimated fatigue life of the C-5A wing has been well documented.

In these situations, inspection of certain critical fastener hole areas becomes mandatory to insure as a minimum that the onset of crack development is detected early enough to avoid catastrophic failure. However, the methods used to conduct such inspections and the sensitivity of the methods (with acceptable reliability) very significantly affect the cost of maintaining these aircraft for several reasons:

a. The most reliable method of inspecting a fastener hole is to remove the fastener, and use an automated or semiautomated eddy current system that rotates a probe in a spiral path through the hole as shown in Figure 9. Such a system applied to holes with good surface finish should be able to detect cracks of 0.030 inch (0.76mm) surface length (0.015 inch-0.38mm radial depth) with good reproducibility. However, the cost of removing the fastener, refinishing the hole and replacing the fastener can be very expensive ($125-$150 per hole). In addition, removal of interference fit fasteners, which are often used in critical holes, can be very difficult and can, in fact cause significant damage to the structure that further increases the repair cost.

b. Inspection of the fastener hole area without removing the fastener is currently conducted using hand-held ultrasonic shearwave methods. The sensitivity and reliability of this method varies greatly as a function of the accessibility of the area, the geometry and the skill of the operator. In general the minimum size flaw which can be detected with any degree of reliability is in the range of 0.25 to 0.50 inch (6.35-12.7mm) radial depth, and only then with slow painstaking efforts on the part of the technician. If a large number of fastener areas must be inspected, the cost can be prohibitive. Moreover, the repair procedure required if such large cracks are detected is more complex, expensive and structurally inefficient. If cracks 0.030 inch (0.76mm) radial depth or less can be detected, it is feasible to drill and ream the hole to a larger size and use an oversize fastener, rather than to install a strengthening patch or replace part of the structure.

Therefore, there has been considerable incentive for both economic and technical reasons to develop reliable methods of inspecting around fasteners without removing them. One effort has been the development of the Rotoscanner* by the Boeing Company for the USAF (Ref 12). This system, shown in Figure 10 utilizes a lightweight, hand-held fixture that is manually centered over the fastener and contains two transducers, properly positioned to generate an ultrasonic shear wave that interrogates the material adjacent to the hole. When activated, the device rotates the transducers 360° around the fastener, once in each direction, with one transducer operating on each revolution to insure detection of cracks even if they are not normal to the hole wall. The signal is then displayed both on the scope of the pulser-receiver unit and on a storage oscilloscope as a circular A scan, clearly showing any crack indications. The transducer locations and angles must be adjusted depending on the size of the fastener and the thickness of the skin. The system is calibrated using coupons of varying thickness containing fasteners with eloxed notches adjacent to the holes to simulate cracks.

This system in its present form has some limitations, the most important of which is that it can reliably inspect the outer layer only. Transmission of the ultrasonic signal across the interface between layers will vary greatly, depending upon the nature of the interface (presence of sealant of variable thickness, etc.). Further, recent evaluations of the unit on various aircraft, including an F-111 fatigue test wing, an A-7 high time aircraft wing, and the T-38 lower wing skin have revealed other shortcomings, including the need to design a more reliable variable transducer locating system, incorporate more reliable mechanical/electrical components and make the unit more rugged. Work to design an improved version is now underway. The potential cost savings offered by a system of this nature, even if limited to outer layer inspection only, are very significant. Cost reductions by a factor of 200 have been projected.

The ability to inspect the inner layers in a multilayer structure without fastener removal offers an even greater technical and economic challenge. However, significant progress in the development of eddy current methods has been made that offers hope of making such a system available in the near future as illustrated in Figure 11.

One approach currently under development by Battelle Memorial Institute's Columbus Laboratory on an AFML contract involves the use of a multifrequency eddy current system (Ref 13). In order to affect a compromise between the use of low frequencies for greater depth of penetration and higher frequencies for better resolution, the Battelle system utilizes three frequencies simultaneously at approximately 90, 300, and 1200 Hz. The resultant complex signal is sensed, sorted into its various components electronically and then the results analyzed by a trained computer network which has the capability to recognize which factors making up this signal are significant, and, in turn, whether there is or is not a crack in the structure. Since the system uses the fastener itself to help project the magnetic field into the structure, it can penetrate fairly deep, at least in the range of 0.4 to 0.5 inch (10.2 - 12.7mm) in aluminum structures. It is being developed to be effective with both steel and titanium fasteners although it is more effective with steel. Flaw sizes in the range of 0.3 to 0.5 inch (7.62 - 12.7mm) have been detected. A modified version now being evaluated shows promise for being able to detect cracks in aluminum structure on the order of 0.1 inch (2.5mm) radial depth. A prototype system should be available by early 1978.

Another eddy current approach for detecting cracks in second layer structures is the use of low frequency eddy currents (Ref 14). In this approach, a special 500 Hz eddy current probe has been shown to be able to inspect around steel fasteners through outer layers of aluminum up to 0.5 inch (12.7mm) thick. Sensitivity at this thickness is reported to be 0.5 inch (12.7mm) radial depth, with cracks down to 0.25 inch (6.35mm) radial depth in thinner structures. This method developed by Boeing, has already been used by a number of airlines and it is reported to have saved them "millions of dollars" by replacing the more expensive radiographic methods previously required. This approach is being further evaluated by Boeing for the USAF to determine its potential for use with titanium fasteners and to see if its sensitivity can be improved.

The importance of developing adequate inspection methods for advanced composite hardware during manufacturing was mentioned previously as a necessary step to insure reliability without the need for prooftesting. There are further significant economic implications in the methods used to inspect composite components at the field and depot level. Although automated inspection methods are now being incorporated during manufacture, inservice inspection is still limited to manual procedures. Figure 12 illustrates the current state-of-the-art ultrasonic inspection of bonded areas on a boron/epoxy horizontal tail in a typical hangar environment. It is a slow process requiring skilled operators. The reliability of this inspection is strongly dependent on visual interpretation of complex signals on the CRT. Automation of certain of these inspections offers great potential not only for increased reliability in the inspection, but also for significant cost savings. Figure 13 shows some potential savings in the manhours required to inspect a typical empennage structure indicating that as much as an 80% reduction in manhours per inspection can be realized. One concept of an ultrasonic system that could perform such an inspection is shown in Figure 14 where automatic data gathering, processing and interpretation can be conducted on an assembled aircraft in a field environment. The AFML is currently initiating a program to design and fabricate a prototype of such a system.

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*Trademark - The Boeing Company

FUTURE POSSIBILITIES

While the generic field of nondestructive inspection as it exists today dates back 35 or more years, most of the current capabilities have been developed in the recent past. The quickening pace of development is likely to continue into the future. Although at this point one can only speculate, nevertheless, a number of future technology advancements are envisioned that should, if exploited effectively, make possible new NDE capabilities having significant direct or indirect economic payoff. A few examples are offered.

Neutron Radiography

The inability of any of the standard NDE methods to detect certain hidden or inaccessible defects has led to a widespread interest in neutron radiography (n-ray). Unlike x-radiography, n-rays, being highly attenuated by certain light elements, are particularly suited to the detection of many important damage conditions such as corrosion hidden under paint or within built-up structure, entrapped water in honeycomb, missing adhesive in bonded structure, residual core material (suitably doped) within complex castings, and others. The n-ray technique was made feasible for practical field inspection applications by the introduction of semi-portable, moderate intensity isotope systems, for example, those using californium-252. However, routine use of such isotope-based n-ray systems continues to be quite limited by several overriding disadvantages. For instance, film exposure times can be excessive (e.g., hours); the necessary safety precautions inhibit other nearby activity; source shielding, transfer and storage requirements are complex and very inconvenient; and finally, the system bulk and inadequate portability limit feasibility of application.

Recent promising development work on ion accelerator n-ray concepts by several groups has indicated the feasibility of a portable, economical system adaptable to in-service inspection requirements which would minimize many of the major disadvantages of isotope systems. For example, the Vought Corporation (Dallas, Texas), under U. S. Army/AMMRC sponsorship, is scheduled to begin work soon to fabricate a prototype scheduled for field evaluation in early 1979. The concept of application of that system is illustrated in Figure 15. Realistic expectations for such a system include 2-minute film exposure times, short inspection setup times, flexible system portability, reduced shielding requirements, elimination of restrictive source handling problems, and greatly reduced training requirements. Once developed, the ion accelerator-based n-ray system should lead to significant economic advantages. Early detection of developing corrosion conditions can reduce significantly the extent, and therefore cost, of repair. The detection of defective adhesive bonding or water entrapment conditions might be used not only to avoid a specific structure failure, but also to introduce remedial manufacturing process changes.

Engine Disk Replacement-for-Cause

The current life management scheme for engine disks is necessarily conservative. These are highly stressed, fatigue life-limited, non-redundant, flight critical components whose unexpected failure must be avoided. According to traditional conservative practice, certain critical disks are replaced at a service life at which there exists a calculated 1% probability that a low-cycle fatigue crack of some very small length has been initiated (Ref 15). Theoretically then, at this design life, 999 out of a population of 1000 disks would be replaced although still possessing an undefined amount of useful life in an uncracked condition which could be as much as 90%.

As the cost of some new disk designs currently being introduced exceeds $20,000 each, the requirement for a more economical replacement scheme based on other than a calculated crack initiation time has become quite evident. Figure 16 illustrates the basic principle of a replacement-for-cause concept being investigated by the USAF. The concept is described in Reference 15 as follows:

> "For a given component, the number of cycles, N_c, required to propagate a crack from an initial size A_o to critical size A_c can be calculated. This number of cycles, N_c, then becomes the upper bound for a cracked component to remain in service. An inspection interval is then established at some fraction of N_c designated N_I. It can be seen that over this interval of time no component containing a crack equal to or smaller than A_o could fail catastrophically. In operation, components would be inspected at the end of the design life, or some fraction thereof, and only those components containing cracks equal to or greater than A_o would be retired. All others would be returned to service. After an additional N_I cycle those components would again be inspected and again all disks with cracks larger than A_o rejected and the remainder returned to service. In this way the crack propagation residual life is continually rezeroed to A_o. By following this approach, components are only rejected for cause (cracks) and the remainder are allowed to operate for the maximum usable time."

In applying a replacement-for-cause scheme, accurate, well characterized NDE techniques are needed in conjunction with reliable crack propagation analyses to produce the maximum economic benefits from disk service life extension, consistent with the degree of conservativeness dictated by safety of flight requirements. A development program will soon begin by the U. S. DOD Advanced Research Projects Agency (ARPA) and the AFML to formulate a comprehensive analysis procedure intended to optimize the economic benefits from putting replacement on a more rational basis. Statistical values for uncertainties in the inspection process, materials performance, stresses, disk usage history and the life prediction model employed will be combined in the analysis. This will allow trades to be made between the cost of disk replacement and the economy of life extension on the basis of inspection cost and risk-of-failure factors.

More Accurate, Versatile NDE Systems

An important long range goal in NDE is to possess the capability to detect accurately and reliably critical flaws while still very small, establishing size, shape and orientation, and to conduct such inspection and evaluation tasks with minimum operator intervention. Early reliable flaw detection may

allow either a repair before more extensive and costly damage occurs, or accurate flaw growth monitoring to give a more economical life management scheme. Noteworthy advances are being made in several technology disciplines which, if properly combined, should provide powerful tools to perform many such NDE functions with unprecidented accuracy and versatility, and, as can be concluded intuitively, with considerable economic payoff potential.

In the field of ultrasonics, for example, researchers are working on several methods to dimensionally characterize flaws. Theoretical modeling studies and experimental measurements of ultrasonic scattering from geometric flaw shapes are being conducted in an effort to establish identifiable flaw type and size signatures (Ref 16). Concurrently, development of direct real time ultrasonic imaging systems using transducer array technology is making progress toward describing flaws whose dimensions are larger than the ultrasonic wave length (Ref 17). The feasibility of an indirect technique using an adaptive learning network (ALN) approach to ultrasonic signal processing has been demonstrated by Adaptronics, Inc. to be capable of identifying, through signal feature analysis, the presence of flaws (fatigue cracks) as small as 0.010 inch (0.25mm) (Ref 18). One can reasonably speculate that from work of the above type will come reliable dimensioning capabilities for small flaws at some point in the future.

The tremendous strides being made in the computer logic and microelectronics fields are expected to have a major impact on NDE. Today, the highly versatile microcomputer, made up of low cost microprocessor components and inexpensive, high capacity memories, provides a powerful computational tool that is ready to be applied to the NDE function. With such logic/microelectronics systems, it appears entirely possible to establish an automated inspection procedure in which preprogrammed command sequences control (1) the probe scanning, including positioning (of the probe or of the part being inspected), (2) frequency and time gate changes, (3) the data acquisition and processing function and finally, (4) the rendering of accept-reject decisions based on preprogrammed criteria. With miniature keyboards, such a system can be controlled and easily reprogrammed and interrogated in real-time by an operator to perform additional information display and data analysis functions.

Another factor which will play a significant part in determining the accuracy and versatility of NDE systems is the establishment of the optimum division of tasks between the human and the NDE instrumentation. Ideally the unmatched sensing and reprogramming capabilities of the human should be combined with the speed, data storage, recall and handling ability and consistency of the computer. Current studies are clearly illustrating, however, that there is no single way of defining the effectiveness of an individual as an inspector. Worse yet, it is still to be determined which human characteristics control an inspector's basic proficiency. Research and development work to clarify behavioral factors related to superior NDE capabilities, as well as methods of motivation, will be necessary to maximize the technical and economic advantages that can be achieved through automation.

CONCLUSIONS

While much of this discussion has centered on a technical description of current high priority NDE efforts in the U. S DOD, it has been the intention to emphasize the economic aspects of this technology. Quantitative examples were given whenever possible. There are many situations in which the NDE function will result in an unavoidable cost increase to insure that structural integrity and mission performance requirements are met. In such cases, economic justification is usually not an issue. On balance, however, the numerous instances where substantial economic payoff has been derived from the effective application of NDE allows one to speculate on the growing number of opportunities that may be exploited in the future.

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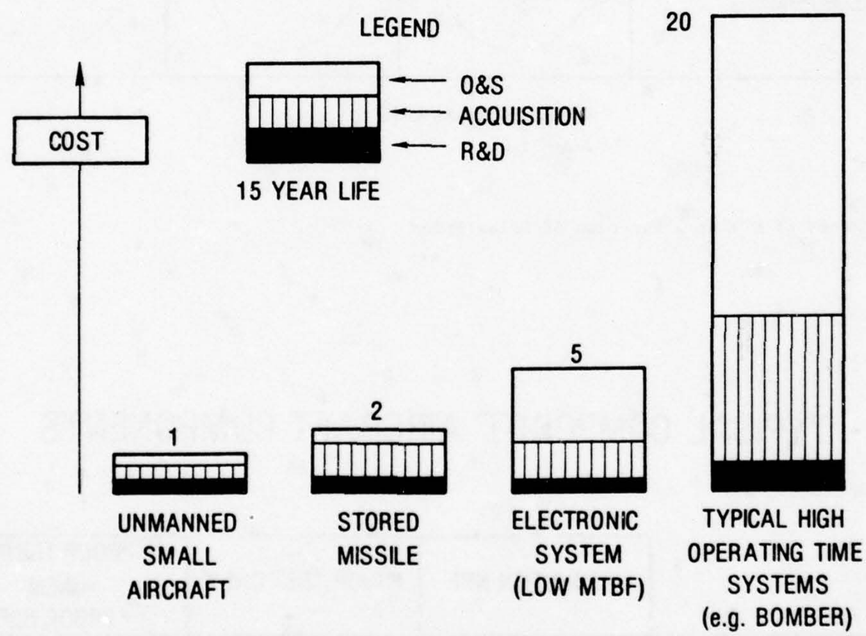


Fig. 1: Relative Life Cycle Cost Comparison

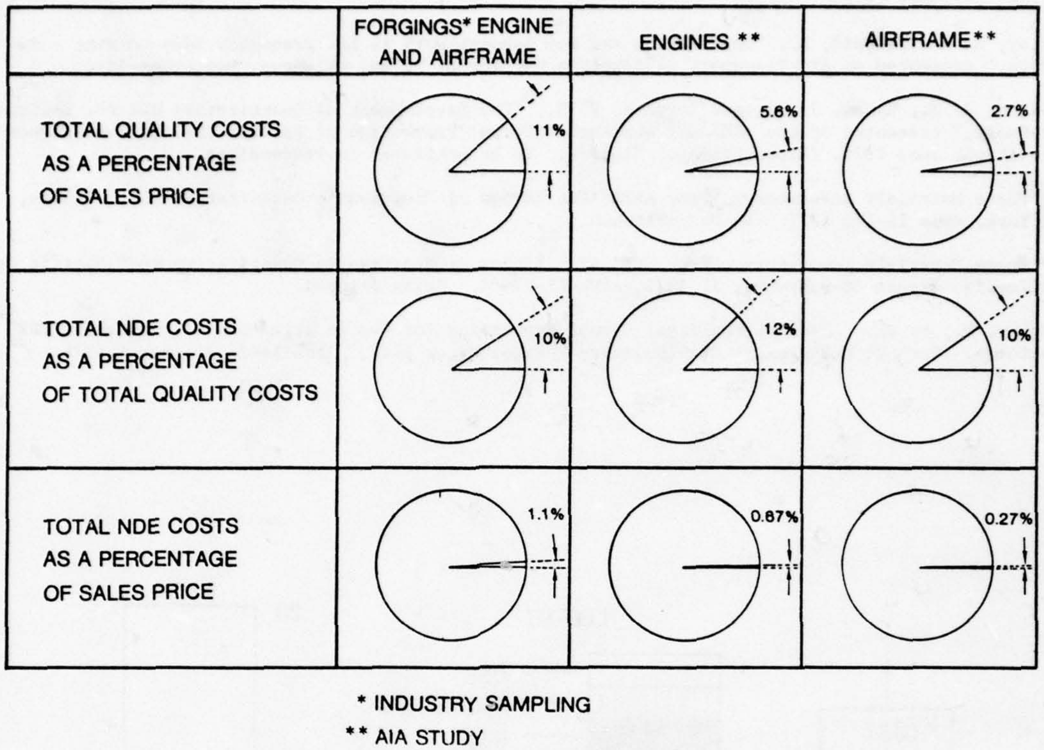


Fig. 2: Cost of NDE as a Function of Sales Price

TYPICAL COMPOSITE AIRCRAFT COMPONENTS

	PRODUCTION NDE	PROOF TEST ONLY	PROOF TEST + AEM + PROOF NDE
VERTICAL TAIL	1	3.75	5.75
HORIZONTAL TAIL	1	2.75	3.4

Fig. 3: Relative Cost Comparison - NDE Versus Proof Test

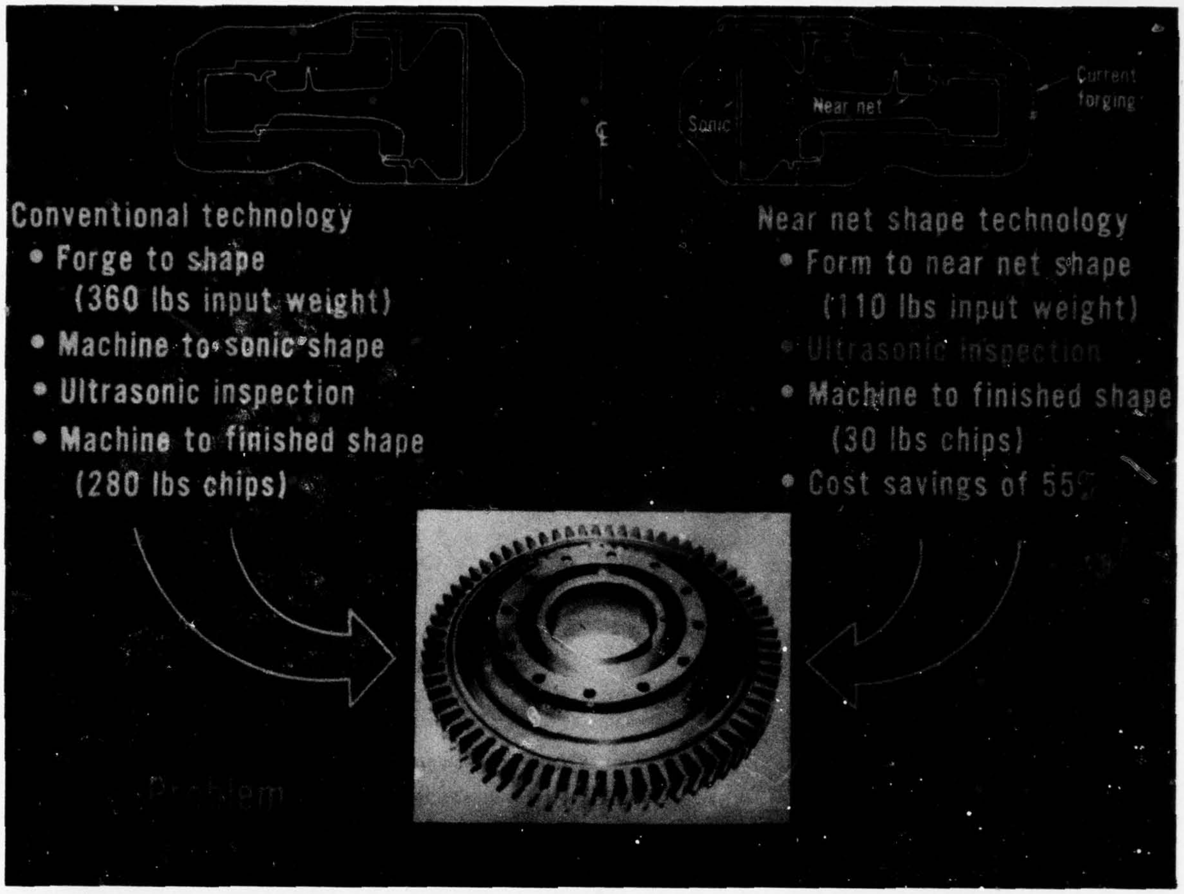


Fig. 4: Manufacturing Near Net Shape Turbine Disks for Reduced Cost

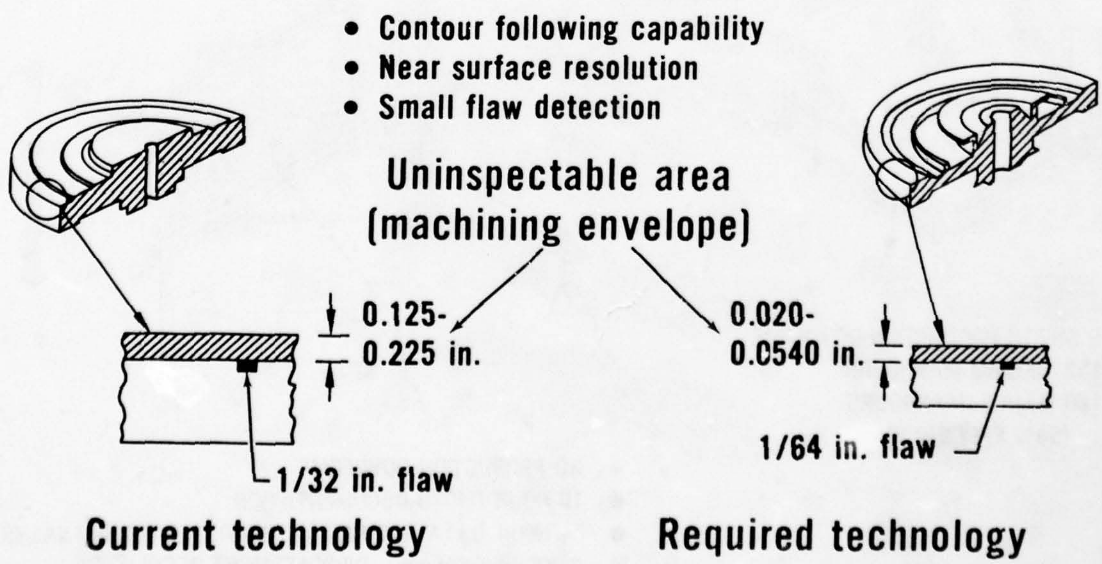


Fig. 5: Required Production Inspection Sensitivity Needs

CAPABILITIES

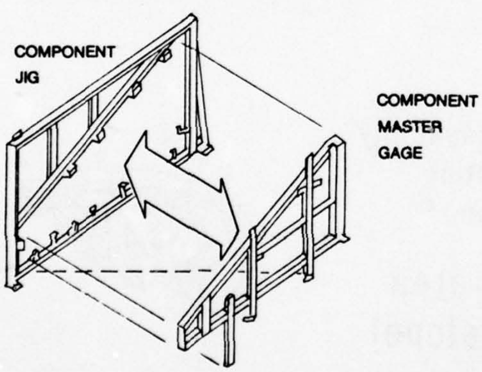
- PARTS TRANSFER/MANIPULATION
- CONTOUR FOLLOWING
- MULTIMODE ULTRASONICS
- PART EDGE FOLLOWING
- MULTIPLE TRANSDUCERS
- DATA STORAGE/RETRIEVAL
- ANALYSIS/DECISIONS
- TAPE LIBRARY
- TRACEABILITY

COST REDUCTION PAYOFF

- CASE STUDY
  - 1000 AIRCRAFT
  - 14 COMPOSITE PARTS EACH
  - PRODUCTION RATE
- TOTAL NDE PROGRAM COST
  - NONCOMPUTERIZED SYSTEM $ 10.8 MILLION
  - COMPUTERIZED SYSTEM $ 2.53 MILLION
- PROJECTED COST SAVINGS 77%

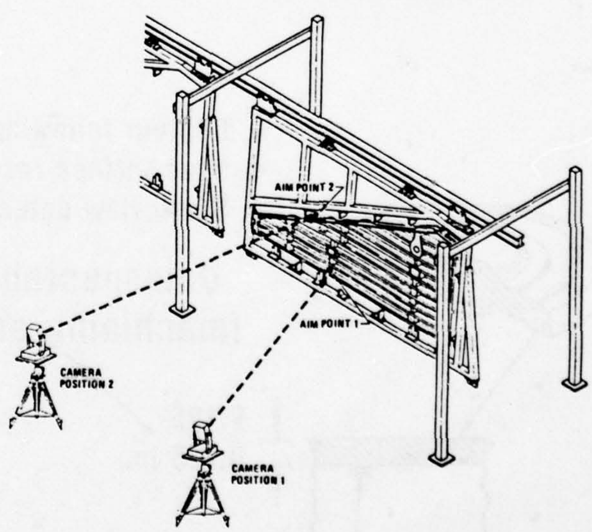
Fig. 6. Computerized Ultrasonic Inspection of Complex Shapes

CONVENTIONAL



- 5 SHIFTS PRODUCTION DOWNTIME
- 152 TOOLING MANHOURS
- 160 MANUF. MANHOURS (50% EFFICIENCY)

PHOTOGRAMMETRY



- NO PRODUCTION DOWNTIME
- 10 HOUR PHOTO DOCUMENTATION
- 74 HOUR DATA ACQUISITION, COMPUTER-AIDED ANALYSIS
- 0.005 IN. (.125mm) DISPLACEMENT RESOLUTION

Fig. 7. Photogrammetric Inspection of Major Assembly Tools

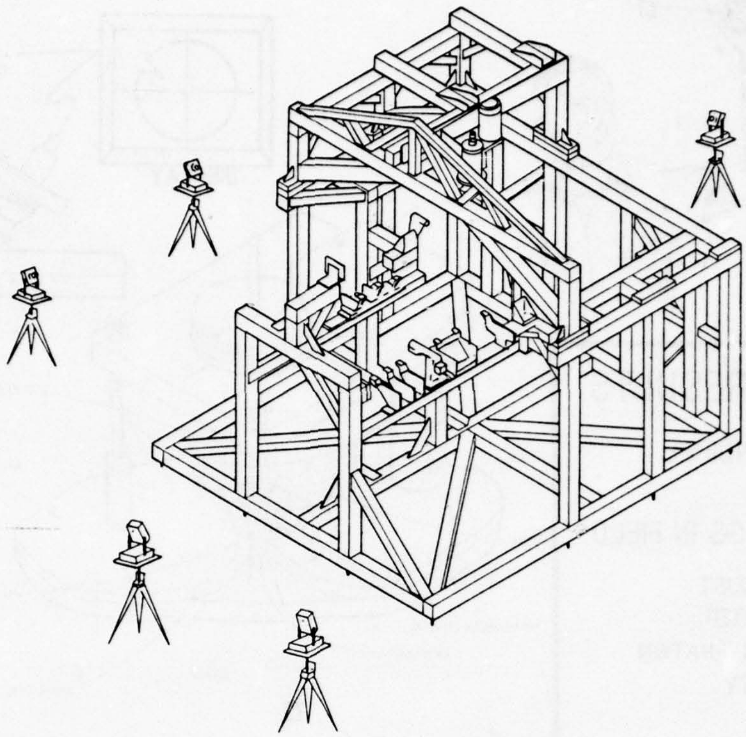


Fig. 8. Photogrammetric Inspection of Complex Fixture

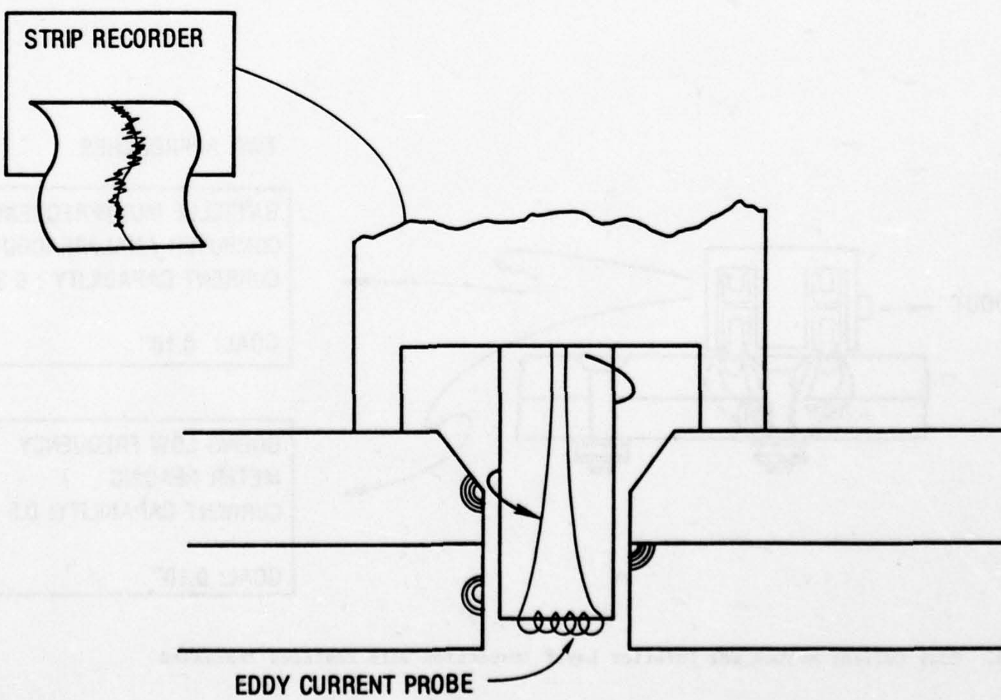


Fig. 9. Semi-Automatic Eddy Current Bolt Hole Inspection

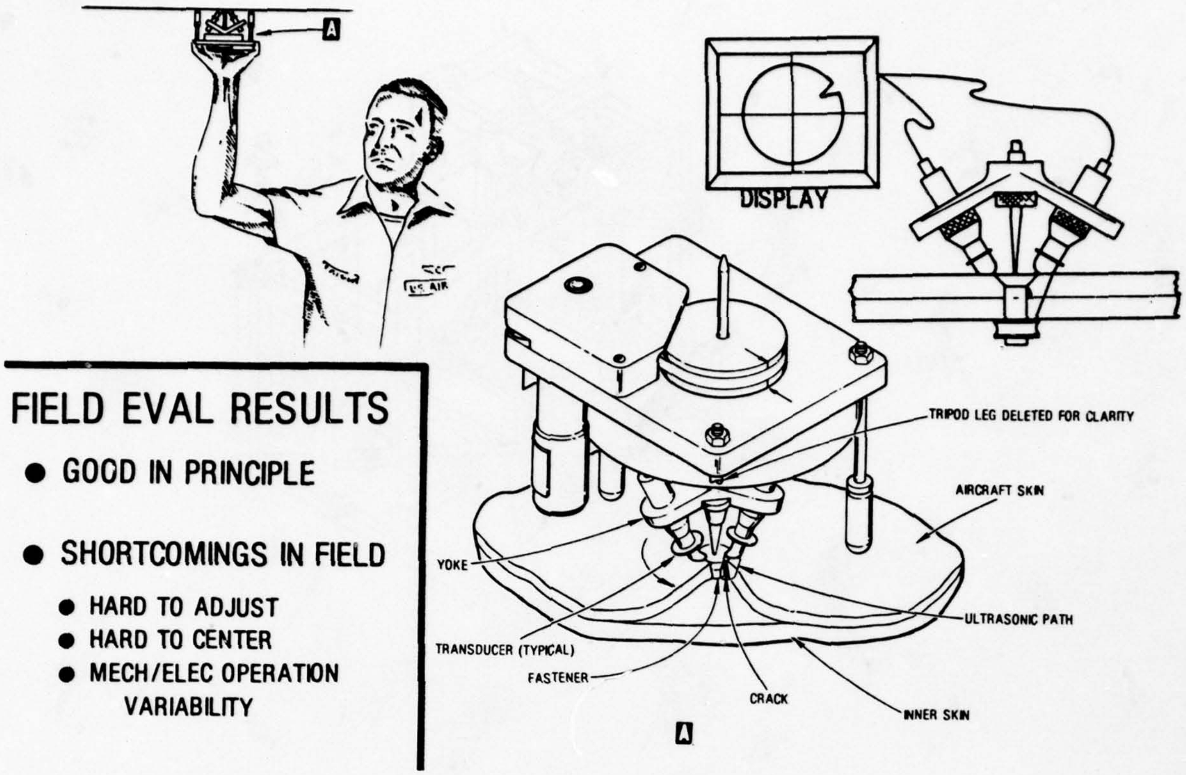


Fig. 10. Ultrasonic Scanner System for Outer Layer Inspection with Fastener Installed

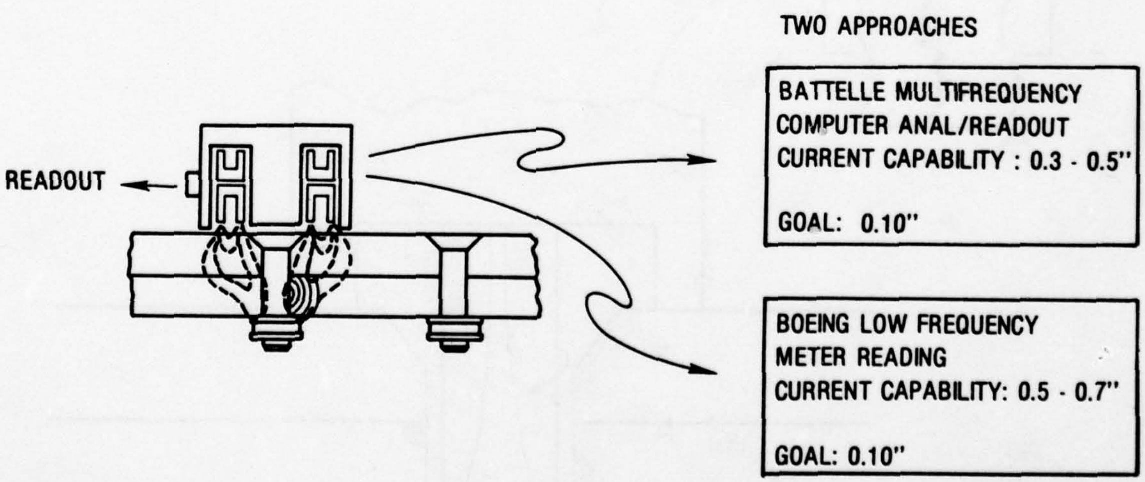


Fig. 11. Eddy Current Method for Interior Layer Inspection with Fastener Installed

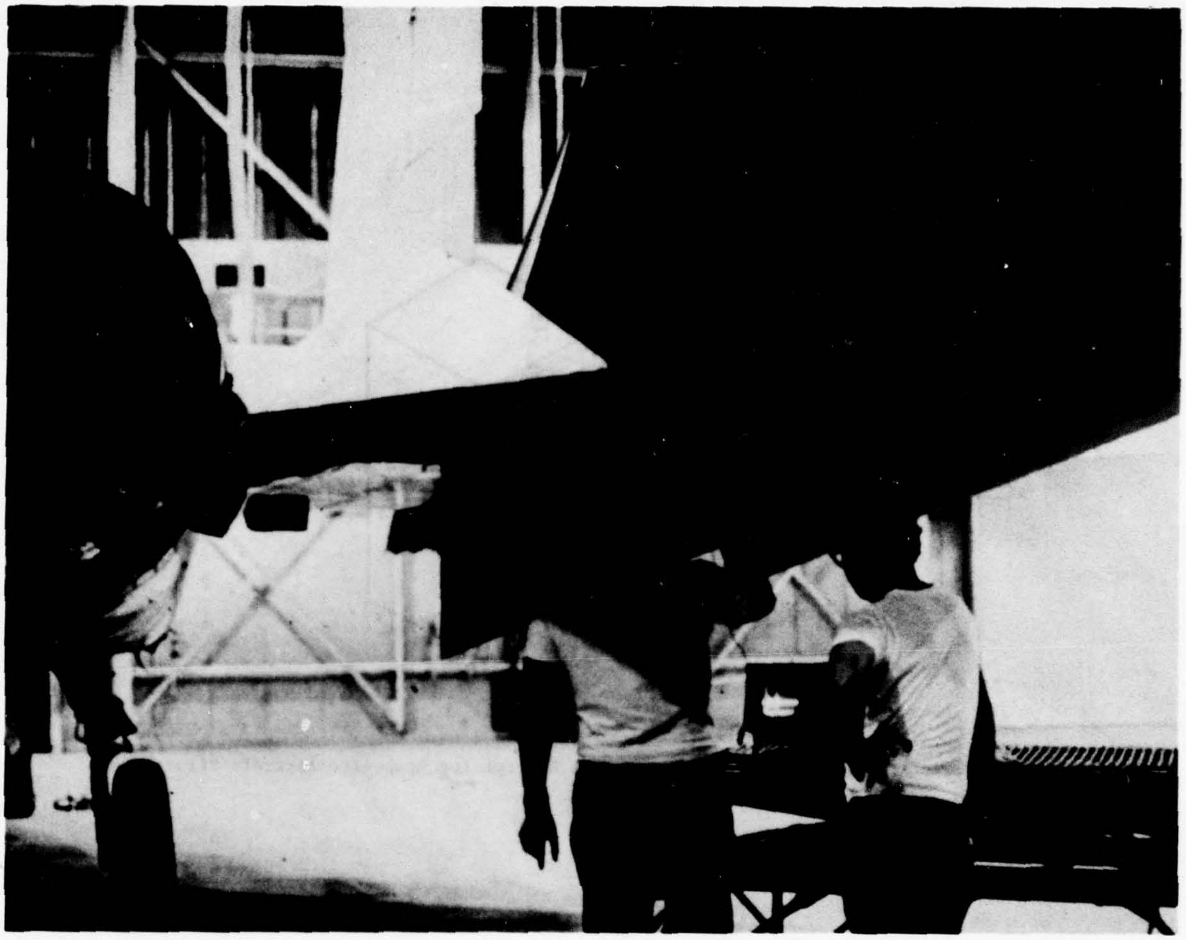


Fig. 12. Current In-Service Ultrasonic Inspection Method for Composite Aircraft Structure

	MANHOURS	
	MANUAL	AUTOMATED
VERTICAL TAIL	10	4
2 HORIZONTAL TAILS	40	6
RUDDER	9	1.5
TOTAL	59	11.5

POTENTIAL MANHOUR COST SAVINGS (PER AIRCRAFT PER INSPECTION) ≈80%

Fig. 13. Potential Cost Savings - Manual Versus Automated In-Service NDE for Typical Composite Aircraft Structures

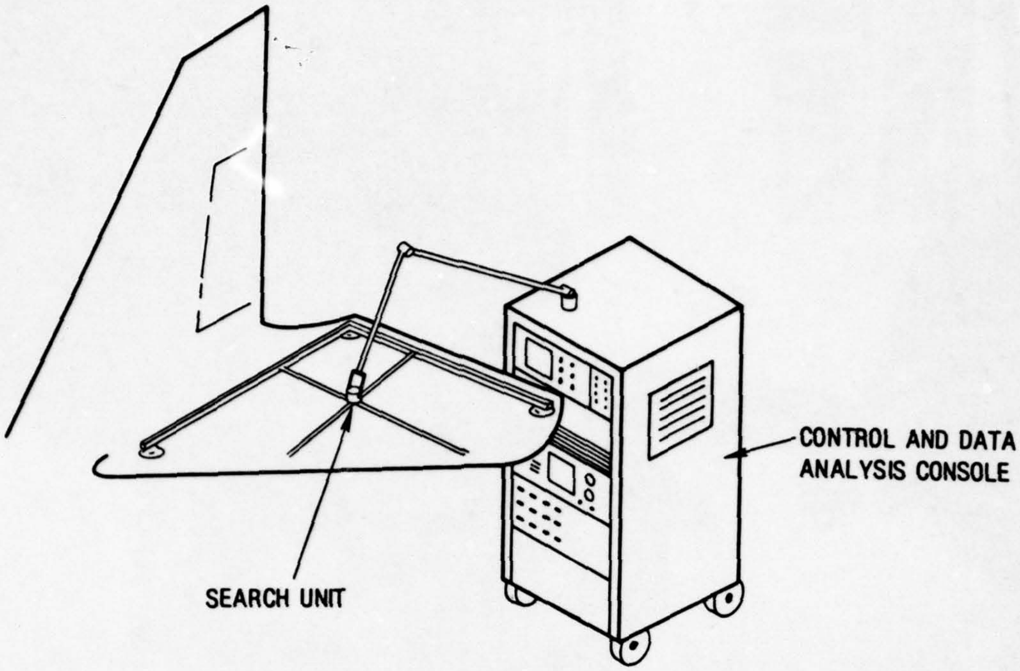


Fig. 14. Automated In-Service Ultrasonic Inspection Concept for Composite Aircraft Structures

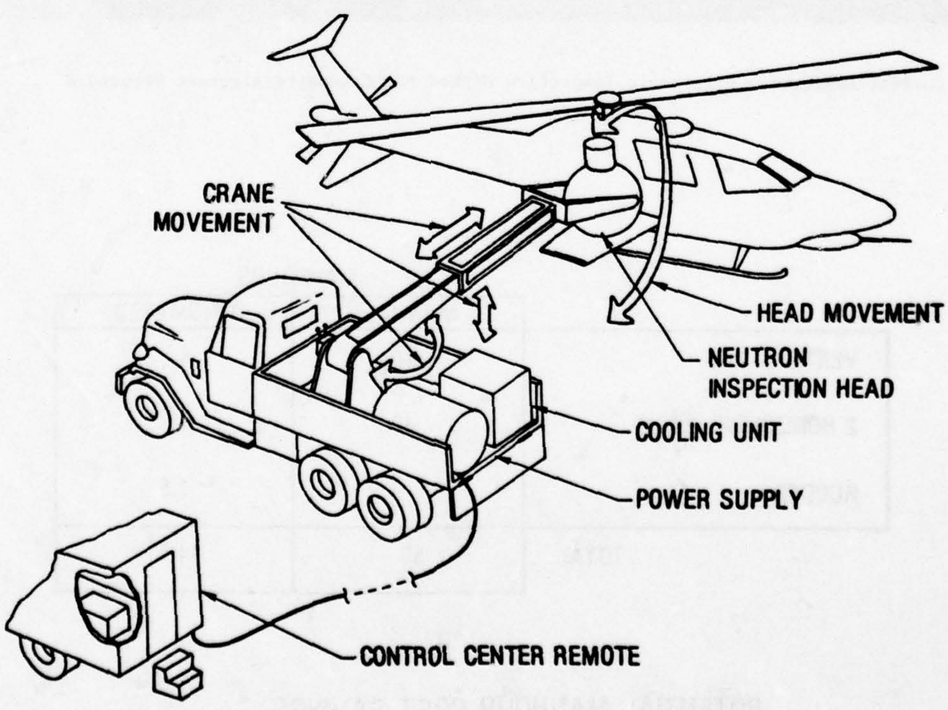


Fig. 15. Field Neutron Radiography Inspection Concept

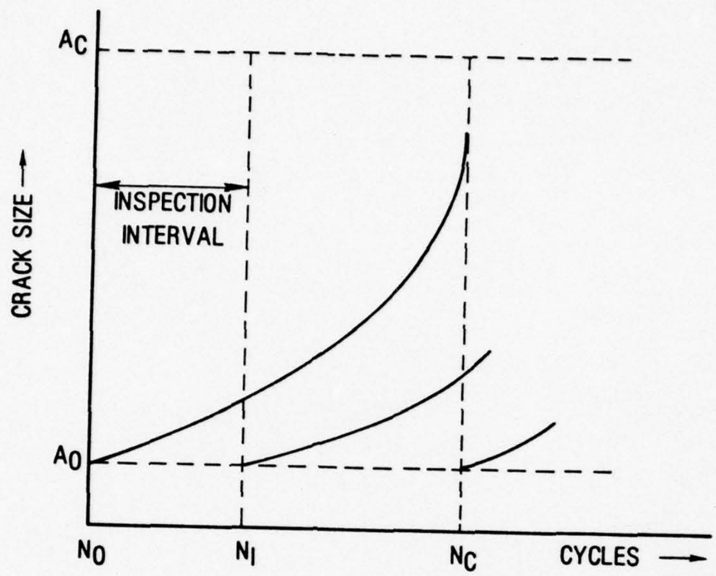


Fig. 16. Engine Disk Replacement for Cause Based on a Crack Growth/NDE Relationship

UNFULFILLED NEEDS OF NON-DESTRUCTIVE INSPECTION OF MILITARY AIRCRAFT

by

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INTRODUCTION

1. The Royal Air Force has been extremely fortunate in that most of its aircraft have been designed nominally to a safe life philosophy and have, in practice, incorporated design features, stress levels and materials which have proved to be damage tolerant to a limited extent. Unfortunately, trends in aircraft design suggest that future military aircraft designed to a safe life philosophy might be much less tolerant to flaws. These trends include:

a. A better knowledge of operational flight profiles and resulting air loads together with the use of computer aided optimisation techniques which enable a more efficient structure to be designed, resulting in higher achieved stress levels and lower hidden reserves of strength. For example, on 3 successive US military transport aircraft designs, the stresses used in 7075-T6 material increased by 30% and 60% respectively over the design stress used for the first aircraft.

b. The increasing use of high strength materials which are decidedly less resistant to cracking and have large variations in fracture toughness and other material properties, and

c. The adoption of design features which have a low resistance to crack propagation (eg a single piece wing skin with integrally machined stringers).

2. Even with our safe life design it has been our experience that cracks occur in Service aircraft earlier than predicted and not always where expected. These almost invariably arise from stress concentrations brought about by poor detail design, by accidental damage, corrosion pits, fretted areas or where the material used is not of the correct specification. It is not surprising therefore that correlation between the predicted fatigue life and that actually achieved is poor. Although large scatter factors are used in an attempt to ensure safety, fatal accidents due to structural collapse under normal loadings have occured at one third of the "proven" fatigue life. Wherever such defects arise it is frequently necessary to impose severe restrictions on flying, or even to ground the fleet while remedial action is taken. An investigation of 6 safe life combat aircraft types showed that, over an 18 month period, there had been 13 defects which caused flying restrictions to be imposed and 40 defects which reduced aircraft availability while they were rectified. On one full scale fatigue test aircraft specimen over 250 fatigue cracks have been identified although only one third of the proposed test programme has been completed. The conclusion is that past and present methods of design, construction and maintenance certainly do not achieve optimum life cycle costs and it is doubtful if acceptable standards of integrity of military aircraft are preserved throughout their lives.

3. The Royal Air Force is therefore adopting a damage tolerant design philosophy similar to but probably not identical with the American MIL SPEC A83444. The basis of such a philosophy vitally depends on an ability to find structural defects before they cause a catastrophic failure. This resembles the familiar "fail safe" design, with one essential difference. In the past catastrophic failures on fail safe structures were avoided by visual detection of the significant defects. There are frequent occasions today where significant defects are smaller than can be detected visually, and in extreme cases, by any known method. As a result Non Destructive Inspection is assuming much greater importance.

UK NDI Military Organisation

4. Until recently, research in the United Kingdom has been proceeding along parallel lines of development in many branches of science, but in a relatively unco-ordinated manner. This, for NDI, has now been resolved by the formation in 1975 of an NDT Co-ordinating Committee whose task is to provide the means of communication and discussion between members on NDI matters and to make recommendations relating to the co-ordination of defence NDI research and policy. Annex A shows the membership which is from some 20 different UK organisations dealing with over 40 NDI methods ranging from optical holography to vibration analysis.

5. The creation of this Co-ordinating Committee provided a focus for general concern that there were unfulfilled needs of NDI that were not getting sufficient attention, not only in research for future generations of aircraft but also in the maintenance of the airworthiness of current aircraft. A working party was created in 1976 to identify and action these unfulfilled needs of NDI. The remainder of this paper is based on the military input to that working party together with some personal observations.

Some Unfulfilled Needs of NDI

6. The need for economy demanded extensions of the lives of our aircraft at about the same time as composite materials were beginning to dominate UK research into aircraft structures. The detection of defects in the metallic materials of UK military aircraft, including Naval and Army aircraft, has therefore been mainly the prerogative of the Royal Air Force, leaving our research and development (R&D) authorities to concentrate on the non-destructive evaluation of composite materials. In retrospect this was a mistake, since uniformed personnel have neither the resources nor continuity in post required to keep pace with the rapidly expanding technology of NDI. The first unfulfilled need is therefore for an effective R&D authority to anticipate in-Service NDI problems and carry out appropriate research to provide the maintenance engineer with timely cost-effective test equipment.

7. It is of interest to note that the United States identified a similar need and started a comprehensive research programme to improve their NDI capabilities. This programme was stimulated by the crash of the F111A and the extremely expensive modifications required to the C5A centre wing. The May 1976 issue of the British Journal of NDT included an excellent review (1) by Mr D M Forney Jr. The USAF are spending about $2.5M in 1977 on NDI research. One of their major programmes into reliability of detection is due to end this year. The results should prove to be of extreme interest to both designers and maintenance engineers.

8. The most serious unfulfilled need of NDI seems to be in the lack of awareness by the structural designer of the need for In-Service inspection. Despite an excellent paper by Lambert and Troughton at the 1967 International Congress on Aircraft Fatigue on "The Importance of Service Inspection in Aircraft Fatigue" (2), many examples can be given where problems have arisen on aircraft but it has proved to be impossible, or extremely expensive in manhours to obtain access for inspection to determine the condition of the remainder of the fleet. For example:

a. A commercial airliner is suffering from corrosion in its fuel tanks. A routine inspection for corrosion damage took 17 men over 3 days to do, a total of about 500 man hours. The airline company developed its own NDT test set which allows 2 men to do the same inspection in ½ hour, a total of 1 manhour.

b. Another example shows a saving of up to 90% of the inspection costs "envisaged" by the designer. The front pressure bulkhead stringer brackets of a large bomber type tended to crack. To gain access for visual examination cost over £3000. By using radiography the items may be examined satisfactorily for only £60.

c. On a combat aircraft it was required to find a critical crack, of length 0.8mm under the head of a countersunk fastener. The limits of present detection capability have been evaluated by an American aircraft company. Annex B shows the very low probability of detection of such short crack lengths, even assuming one knows where to look. In the event an aircraft was lost due to wing failure.

d. Almost as bad is the example of an helicopter tail support for the tail rotor. What appears to be a relatively straightforward design is a completely enclosed box structure with no internal access at all.

9. These examples are only a few from many and should vividly illustrate that generally, in the past, aircraft designers have not paid sufficient attention to the inspection problem. A code of practice needs to be specified and internationally agreed by aircraft designers. This should require them to consider how each of their designs are to be inspected, initially during production to guarantee the initial flaw assumptions made, and then during operation so a good probability exists of detecting significant degradation in time to effect an economic repair and certainly before catastrophic failure becomes likely.

ERGONOMICS

10. This leads conveniently to another unfulfilled need, that of knowing the detection capabilities of our operator/equipment systems. An NDI technician's performance deteriorates with time at the job since he often works in cold, wet, cramped conditions on a repetitive boring task with equipment of problematical detection capability. Annex C shows how reliable detection becomes less probable with cracks less than about 3 mm in length. Medical research is required to determine when the technician's level of performance drops to unacceptable levels under specific conditions. A good example exists with one type of transport aircraft (not of UK origin). It is necessary to inspect some 4000 fastener holes on each aircraft once every 9 months to detect any crack approaching 1 mm long in the material under the head of any of the countersunk fasteners. The operator is required to work out in the open air. When checking the 2000 fastener holes in the lower surface of the wing the NDI probe has to be held above the operator's head, manipulating it quite precisely, yet generally at the same time having to watch the test set located at his feet for signs of a defect indication. Estimates are that he has about a 15% chance of finding significant defects during this two day operation. Clearly he has a reasonable chance of detection on the first fastener but one hesitates to estimate what his efficiency is at the 1999th fastener. Much better detection capability is possible if the fasteners are first removed but a conservative estimate is about $100 as the cost

of removing and replacing each fastener. It is obvious that urgent research is required into the ergonomics of NDI test equipment. Annex D gives the main NDT methods in use in the RAF and the numbers of each technique issued during the last three years. In most of these there are limitations imposed by the ergonomics of the task. Effective research would be amply rewarded with faster, more reliable inspection.

11. A further way of improving the ergonomics of NDI and at the same time improving the probabilities of detection lie in automation. There is a need to plot the progress of fatigue damage from its inception, whether it originates from a discontinuity, from grain boundaries, a material dislocation, or even from a minute initial flaw present in the structure on delivery. It is hoped that automation will minimise reliance on the subjective judgement of the technician and also provide permanent records of crack growth rates so important in a damage tolerant design philosophy.

CURRENT PROBLEMS

12. The above example of the 2000 fastener holes to be inspected also illustrates the most serious practical problem, that of locating and sizing small cracks (1 mm) beneath fasteners, in fastener holes and in multi-laminate construction. One of the big problems in inspection of aircraft is the large area to be examined, often in inaccessible locations. The structures are so complex that it is quite possible to miss large surface cracks despite careful visual examination, particularly when specially treated and painted surfaces are involved. There is an unfulfilled need for a general search tool. At its simplest this could be an illuminating steerable flexible fibrescope, possibly led through built-in tubes in the structure to permit visual access to otherwise inaccessible areas. With the exceptions of visual inspection, and the Blade Inspection Method on helicopters, the NDI technician still needs to be told fairly precisely where to look and what to look for if he is to have a reasonable chance of finding small defects. Even then, reaction of the test equipment to specific types of defect can only be determined by adjusting the sensitivity of the equipment in relation to a fully representative specimen defect in a similar piece of structure. Only in this way can spurious indications be allowed for in the actual inspection technique adopted. There is therefore an unfulfilled need for an ability to manufacture representative defects so NDI technicians can calibrate test equipments for optimum sensitivity before searching for defects in aircraft.

13. In the long run, a search tool is needed which will monitor complete aircraft for significant defects at negligible cost. Perhaps the answer lies in the use of acoustic emission or perhaps in holography. Whatever the answer much research is urgently required if the need is to be met in a reasonable timescale.

THE IDEAL IN NDI

14. It may be helpful to define the ideal NDI situation. If an airframe, its engines and systems are all capable of operating to the required performance throughout their lives then the operators do not wish to take any action at all. Only if that performance is threatened do we wish to know and then only passively. Ideally we need cheap, perfect, automated in-flight monitoring. If a significant defect occurs we wish to be immediately alerted, the pilot should be given guidance on his conduct of the remainder of the flight, whilst the maintenance engineer on the ground needs an automatic readout on the precise location, size, orientation, significance, rate of propagation and time to economic repair of the defect. The time to economic repair is important since much money is wasted replacing components when, if only the defect had been identified early enough, it may have been possible to eliminate it, say by reaming out a cracked fastener hole to the next oversize. A typical illustration of crack growth emphasises this point. Fracture mechanics predict for a particular structural application that:

a. if an initial detectable flaw size is 0.25 mm the crack will be 25 mm long after a further 3000 flights.

b. provided reliable detection of the flaw can be made when it is only 0.125 mm long ie half of the previous, then it will only grow to 0.6 mm in length after the same number of additional flights. This second case is clearly a much easier situation for the maintenance engineer to repair at much less cost.

This requires an accuracy and reliability of detection quite beyond present day capability. Periodic monitoring of such cracks will then determine when best to initiate remedial action. In this way airworthiness may be maintained at minimum cost and at the same time avoid the many crisis management situations which arise under the safe life design philosophy.

CORROSION

15. One must not be misled into thinking that a defect occurs solely due to fatigue damage. Corrosion is becoming more important, not only as an initiation site for fatigue but in its own right as the lives of aircraft fleets continue to be extended on economic grounds. Some individual aircraft are nearly 40 years old and some operational fleets of aircraft are about 25 years old. An unfulfilled need exists to identify and monitor the progress of corrosion and to assess its significance.

RESIDUAL AND THERMAL STRESS

16. These are some of the current needs of NDI but there is a need for more fundamental thinking. For example, what residual stresses are accidentally built into an aircraft during manufacture? As an example, inaccurate assembly methods have introduced higher mean stresses in a combat aircraft centre section than the designer intended. As a result stress corrosion cracking has occurred unexpectedly introducing extremely high inspection workloads to ensure aircraft safety. There is a need for NDI test sets for use during manufacture to identify such unintended residual stresses, and to identify stress corrosion cracking at an early stage. Degradation of material properties may follow thermal cycling. How can this degradation be measured?

ADHESIVE BONDING

17. It would appear that no NDI method has yet been found which will give confidence that work pieces are correctly bonded together in manufacture. Neither is there an NDI method which will monitor the integrity of the bond under service conditions. There is clearly a need for effective NDI of adhesive bonding and its deterioration in Service. The problem is not if the structure is still bonded together but what residual strength is there in the bond which appears to be intact.

OTHER NEEDS

18. Discussion so far has in the main been related to aircraft structures. Experience shows that at least as many aircraft are lost due to engine failure as to structural collapse. Several techniques are in use in the Royal Air Force to monitor the condition of engines. Until recently these have been confined to very limited visual inspection and of monitoring wear in the engine by examining the particles circulating in its lubricating fluids. Vibration analysis has now been introduced as an NDI method. It promises to be a powerful tool in identifying defective rotating components. Despite this advance there still remains the need to detect at an early stage, foreign object damage, blade creep, turbine disc or blade cracking, combustion chamber cracking, or indeed the many modes of possible failure present on current designs of aero-engines. Other problems exist in finding incipient defects in hydraulic and fuel pipelines. Should discussion be confined to materials? In the field of NDI can no one produce a test set to detect the source of leaks of fluids, or even the state of charge of batteries?

TRAINING, CERTIFICATION AND STANDARDS

19. Even with excellent NDI equipment the detection of significant defects relies currently on the skill of the technician. It is disturbing to read that the President of the American Society for NDT quotes an NDI expert as saying that the NDT certification of some of the military inventory as pure falsehood. There is a need for universal support for the creation of international standards for training, certification and maintenance of standards for all NDI technicians be they military or civilian, engaged in aerospace or any other engineering discipline.

CONCLUSION

20. For the more conventional metallurgical areas, we foresee future problems arising in the NDI of inertial bonding of dissimilar materials, the diffusion bonding of titanuim alloys, of materials manufactured through powder-type routes and also in determining the effects of thermal degradation and work hardening. There seems little doubt that future aircraft will incorporate considerable composite structure. The Royal Air Force has no experience in the NDI of composite materials. However the problems of determining the degradation of composites are so different from those associated with metals that NDI research has been progressing in parallel with the development of composites. It is hoped that aircraft designs in composites will have NDI techniques specified as part of their airworthiness certification. This paper has tried to illustrate some of the NDI problems facing the engineer concerned with maintaining the airworthiness of military aircraft. In the time available only a few of the more urgent needs have been considered but one hopes that the potential of NDI will soon receive the attention it richly deserves as a means of optimising not only airworthiness but life cycle costs.

References

1. 'NDI in the USAF' D M Forney Jr British Journal of Non-Destruction Testing May 76.

2. 'The Importance of Service Inspection in Aircraft Fatigue' Lambert and Troughton. Proceedings of 1967 ICAF Symposium.

3. 'Potential Developments in NDT' Dr Halmshaw British Journal of Non-Destructive Testing. January 77.

ANNEX A

Officers & Membership of the Co-ordinating Committee for NDT at January 1976

Chairman:	Head of Materials Department Royal Aircraft Establishment FARNBOROUGH Hants	Aldershot 24461, Ext 2029
Secretary:	AQD Laboratories Harefield Uxbridge Middlesex UB9 6BB	Harefield 3161, Ext 13

Membership

Abbreviation	Establishment/Branch
AML	Admiralty Materials Laboratory
AWRE	Atomic Weapons Research Establishment
DR MAT	Directorate of Research, Materials
MVEE	Military Vehicles & Engineering Establishment
NAML	Naval Aircraft Materials Laboratory
NCRE	Naval Construction Research Establishment
RPE	Rocket Propulsion Establishment
RAE	Royal Aircraft Establishment
RARDE	Royal Armament Research & Development Establishment
AQD	Aeronautical Quality Assurance Directorate
DG Ships	Director General, Ships
DNOS	Directorate of Naval Ordnance Services
EQD	Electrical Quality Assurance Directorate
MQAD	Materials Quality Assurance Directorate
QAD/FVE	Quality Assurance Directorate (Fighting Vehicles & Engineer Equipment)
QAD/W	Quality Assurance Directorate (Weapons)
CSDE	Central Servicing & Development Establishment (RAF)
Air Eng	Ministry of Defence Air Eng 30d (RAF)
REME	Workshop Technology Branch, REME Support Group
	Ex-officio Member
SBAC	Society of British Aerospace Companies

NB. To contact the appropriate representative at each of the above establishments an initial approach should be made to the Secretary of the Committee.

TABLE I

ESTABLISHMENT' INTERESTS & ACTIVITIES

METHODS OF NON-DESTRUCTIVE TESTING

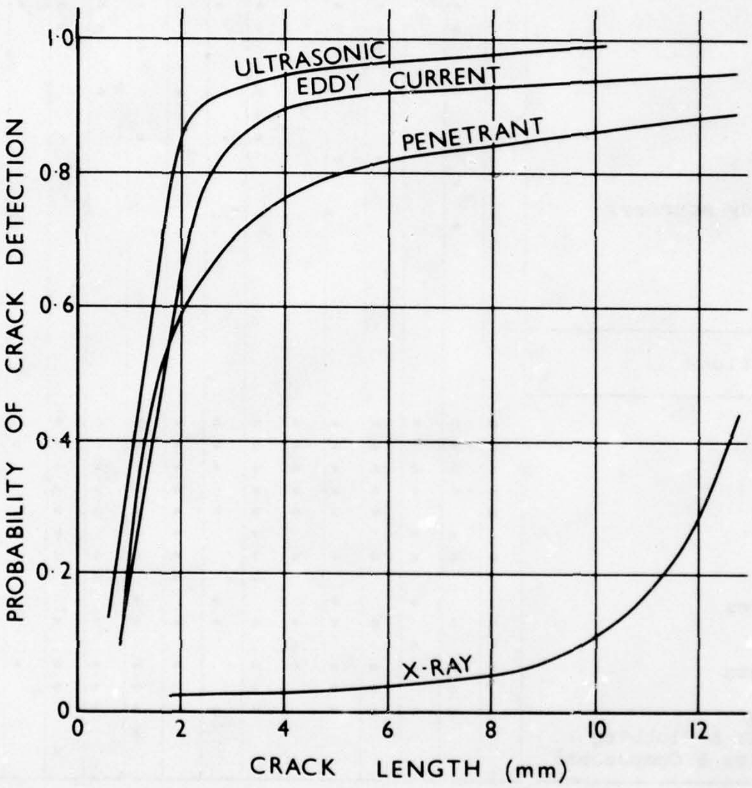
Methods	Establishments																	
	AML	AWRE	DR MAT	MVEE	NAML	NCRE	RPE	RAE	RARDE	AQD	DNOS	EQD	MQAD	QAD(W)	DG SHIPS	CSDE	AIR ENG	REME
Radiography, Low Energy X-rays		*			*		*		*	*		*		*	*	*	*	
" Med " "		*			*	*	*	*	*	*	*	*		*	*	*	*	
" High " "		*					*		*	*	*			*				
" High Definition X-rays		*			*				*	*				*				
" Gamma-rays		*				*	*	*	*	*	*	*		*	*	*	*	
" Neutrons		*							*	*								
Fluoroscopy, Conventional		*						*	*	*	*	*			*			
" Image Intensifier/ Amplifier		*					*		*	*								
" Cine Recording									*	*								
" Video Tape Recording		*					*		*									
Luminescent Panels		*								*								
Image Enhancement		*							*					*				
Thickness Gauging, Beta-rays		*								*		*		*				
" " Gamma-rays		*													*			
" " X-rays		*																
Ultrasonics, Reflection		*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*
" Transmission		*	*		*	*	*	*	*	*	*			*	*	*	*	
" Resonance		*					*	*		*				*				
" Immersion		*	*			*	*	*	*	*	*			*	*			
" Holography							*											
Eddy Currents, Low Frequency	*	*		*	*	*	*	*		*				*	*	*	*	*
" " High "	*	*	*	*	*		*	*	*	*	*			*	*	*	*	*
Magnetic Particle	*	*		*	*	*	*	*	*	*	*	*		*	*	*	*	*
Penetrants		*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	
Stress Wave Emission	*	*	*	*			*	*	*	*					*	*	*	
Vibration Analysis										*						*	*	
Polarised Light Interferometry								*					*					
Corrosion Monitoring			*															
Non-contact Profile Measurement														*				
Training - Radiological Methods									*	*				*	*	*	*	
" Radiation Safety Practice					*					*				*	*	*	*	
" Magnetic & Penetrant Methods										*	*			*	*	*	*	
" Electrical Methods										*	*			*	*	*	*	
" Ultrasonics										*						*	*	
Assessment of Operator Competence										*	*			*	*	*	*	
On-site NDT				*	*			*	*	*	*			*	*	*	*	*
Visual Aids - Photography				*			*		*	*				*	*	*	*	
" " Fibre Optics				*											*	*	*	*
" " Introscopes				*			*	*		*	*			*	*	*	*	*
" " CCTV							*								*	*	*	
Ultra-violet Fluoresence													*	*		*	*	*
Optical Holography		*					*	*										
S.O.A.P.													*			*	*	

TABLE II

ESTABLISHMENTS' INTERESTS & ACTIVITIES

MATERIALS & APPLICATIONS

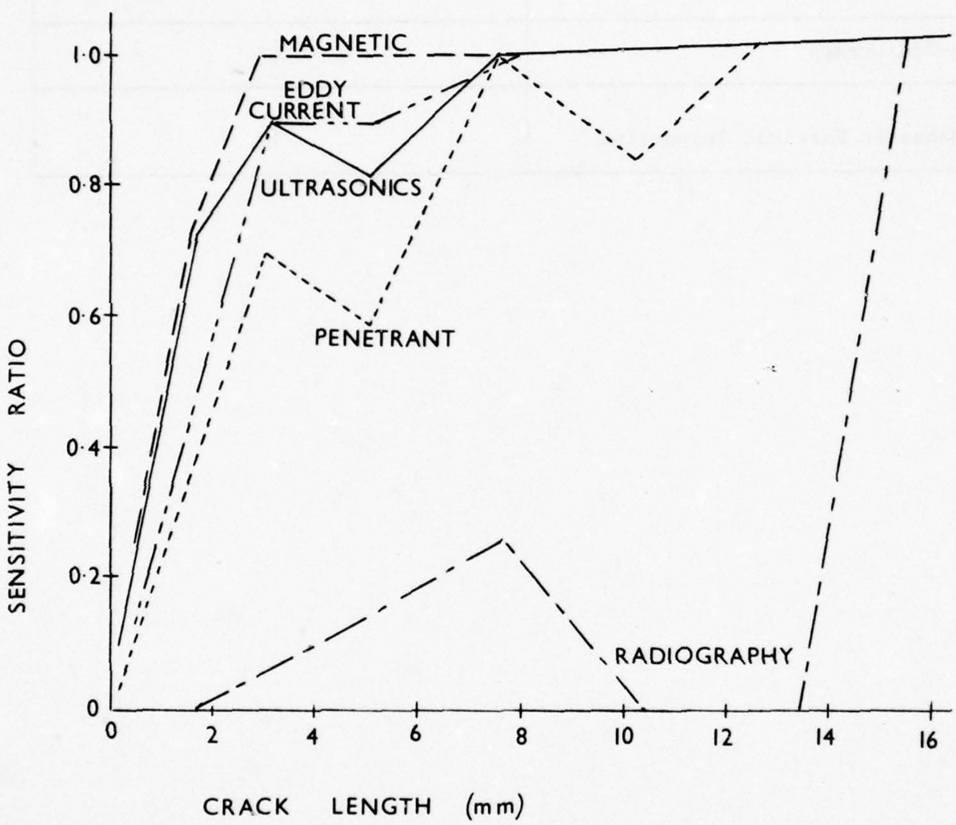
	Establishments																	
Materials	AML	AWRE	DR MAT	MVEE	NAML	NCRE	RPE	RAE	RARDE	AQD	DNOS	EQD	MQAD	QAD/W	DG SHIPS	CSDE	AIR ENG	REME
Ferrous Metals	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*
Non-Ferrous Metals, Heavy	*	*		*		*	*		*	*	*	*		*	*	*	*	*
" " " Light	*	*		*	*	*	*	*	*	*	*	*		*	*	*	*	*
CFRP	*	*	*	*			*	*		*								
GFRP	*	*	*	*	*	*	*	*	*	*	*				*			
Plastics	*	*		*	*		*	*	*	*	*	*	*	*	*			
Rubber		*		*	*		*			*	*	*			*			
Textiles				*	*					*								
Adhesives			*											*				
Explosives		*					*		*		*							
Si C Impreg							*											
Durestos							*			*				*				
Lubricants				*	*										*			
R-A Materials (other than Y-rady sources)		*													*			
Fissile Materials		*																
Applications																		
Sheet	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*
Extrusions	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*
Tubing	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*
Forgings	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*
Castings	*			*	*	*	*	*	*	*	*	*		*	*	*	*	*
Mouldings	*	*	*	*			*		*	*		*	*	*		*	*	
Weldments	*	*	*	*	*	*	*		*	*	*	*		*	*			*
Rocket Motors							*		*		*			*				
Aircraft Structures			*		*			*		*						*	*	
Fabrications	*	*		*	*	*	*	*	*	*	*	*		*	*	*	*	
Ship Hulls	*		*			*									*			
Finished Components	*	*	*	*	*	*	*		*	*	*	*	*	*	*		*	*
Assemblies		*		*	*		*		*	*	*	*		*	*	*	*	*
Bonded Structures		*	*	*	*		*	*		*	*			*	*	*	*	
Survival Equipment & Clothing										*						*	*	
Electronic Circuits & Components												*						



RELIABILITY v CRACK LENGTH FOR FOUR NDT METHODS

(Martin Marietta)

ANNEX C



SENSITIVITY OF THE FIVE NDT METHODS TO SURFACE FLAWS IN PROGRAM SPECIMENS (after H. Southworth)

ANNEX D

MAIN NDI METHODS IN USE IN THE ROYAL AIR FORCE AND THE NUMBER OF EACH TECHNIQUE ISSUED IN A 3 YEAR PERIOD

Technique	Number Issued Jan 74 to Dec 76
Eddy Currents	114
Ultrasonics	71
X-Radiography	47
Magnetic Particle Inspection	45

SESSION I
Rapporteur's Report

by

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The first four papers presented at this meeting are concerned with the overall problems of non-destructive inspection and with current and future needs. While each of the papers approaches the subject from a different viewpoint and with different emphases, there is a remarkable coherency and a number of recurrent themes. Perhaps the most important of these is the need to make designers more aware of the needs and problems of the inspector and of the potential economic benefits of properly planned inspection schemes.

Attention to the need for awareness on the part of the designer is drawn by the first paper presented, that of Bolis. He emphasizes that inspection is not a subject that can be treated in isolation. The problem is not simply that of finding cracks or other defects but also that of assessing their consequences. It is important therefore that the inspector be told where and when to look for defects and that the loop be closed by a proper evaluation of his findings by means of fracture mechanics techniques. Bolis suggests that a more appropriate term to cover the problem is "non-destructive evaluation".

The topic of the evaluation of the consequences of cracks is taken up by Antona with particular reference to damage tolerant design. The latter demands close cooperation between designer and inspector.

The paper by Kent presents several examples of the physical difficulties of inspecting current aircraft and of the high costs of these inspections. In some of his examples, operators have been able to devise inspection techniques that are orders of magnitude faster and cheaper than those suggested by the manufacturer. In others, effective inspection is virtually impossible. Clearly there is a case for better dialogue between designers, inspectors and operators.

While the need for designers to inform inspectors of anticipated cracks is clear, it is an unfortunate fact that many unanticipated failures have occurred in the past and more will undoubtedly occur in the future. While some of these failures have been the result of oversights on the part of the designer or of manufacturing errors, by no means all of them can be attributed to the manufacturer as he has no control on how his product will be used. As one speaker pointed out in the discussion, even a properly conducted fatigue test on a multi-role aircraft will not show up all possible failure modes. Furthermore there are countless possibilities of accidental service damage of many different kinds. There is, therefore, a potential hazard in a designer being too specific in laying down his requirements for inspections. The inspector must monitor the whole aircraft for significant defects, both anticipated and unanticipated. To achieve this, as Kent points out, he needs a search tool that is easier and faster to use than the human eye upon which he is now dependent. There are possibilities that acoustic emission or holography might provide useful tools in this context.

Another recurring theme in the papers is that of the problems of inspecting fasteners. The defect sizes of importance in the structures that are joined are often so small that they are covered by the fastener heads. The cost of removal and replacement of individual fasteners for inspection of the members that they join is high and the large numbers involved make the total cost prohibitive. These same large numbers pose a major problem in that when conducting conventional ultrasonic inspections with hand-held probes, operator fatigue becomes a serious consideration in the reliability of the inspection. The problem is frequently aggravated by the lack of ergonomic considerations in the design of the test sets or in the planning of the inspection schemes. The example quoted by Kent, of a hand-held probe being used on a row of fasteners in the lower surface of a wing skin with the indicator virtually at the operator's feet should be sufficient to convince one that better methods are an urgent need.

In this latter context, the paper by Forney and Cooper shows hope for the future in that it reveals a number of promising attempts at automating the non-destructive inspection process including not only both ultrasonic and multi-frequency eddy current scanner systems for fasteners but, perhaps more exciting, a fully automated computer-controlled ultrasonic inspection concept.

The economics of non-destructive inspection have not received much attention in the past and for this reason the paper by Forney and Cooper makes particularly interesting reading. While the costs of developing full automated systems is high, the payoff in terms of speed and reliability of inspection can be such that they are fully justified and cost-effective. The introduction first of the mini-computer and now of the micro-processor have opened many doors for automated inspection, decision making and record keeping and it is in these directions that we can perhaps hope to see major advances in the future.

DISCUSSION SUMMARY
Session I

C.W.Hope (UK)

We can present ourselves from the NDT side of industry as a medium for co-ordination and interpretation of structural information for the following reasons:

First of all, we are involved in design to ensure inspectability of the end product.

Secondly, we have the means of establishing the structural proof testing data as a monitor for failure initiation and crack propagation, leading to realistic specifications of acceptance levels for defects.

Thirdly, we are able to anticipate and find defects at an early stage of production to ensure a suitable product at the most economic cost.

Finally, we are involved in product support: in the light of the knowledge obtained in the three points already mentioned, we can derive practical in-service NDI techniques. I therefore submit that NDI is the only discipline involved in all these four steps from the design to the death of a product.

T.Sharples (UK)

The USA paper (Forney, Cooper and Rowand) emphasised the need for the development of automated ultrasonic techniques. Are these able to detect defects only in the first layer, or can we expect them to detect cracks in the lower layers?

Wing Commander Dawson stated that research in the USA led to the conclusions that there is only a 20% probability of finding a 1 mm crack irrespective of material, position in the structure, or technique. Since Mr Forney said we can expect to find cracks of 0.4 mm, perhaps the apparent discrepancy between these statements could be clarified.

D.M.Forney (US)

With regard to the problem of finding cracks in two layers, our approach to this problem is to use a multi-frequency eddy current probe which is in development using three separate frequencies simultaneously of 90 Hz, 300 Hz and 1200 Hz. We use a computer to analyse each of the three return signals, and we are able to identify combinations of perturbations in the eddy current signal that indicate the presence of a crack in the second layer. Thus we are able to combine the depth penetration of the low frequency signal with the sensitivity of the high frequency signal. At present we are able to detect flaws of the order of 0.3 in.

A second approach is to use a low frequency (about 500 Hz) eddy current. This is a process which is being developed by the Boeing Company for commercial application, and the probe can now detect a crack about 0.5 in in length. Both of these probe designs are expected to be ready for field evaluation by the end of this year.

When I referred to finding flaws of 0.4 mm in length, I was referring to flaws in the interior of a solid piece of structure such as a turbine disc. I think Wing Commander Kent's paper was referring to flaws coming from bolt holes, which is a quite different kind of problem.

R.Dawson (UK)

In the Royal Air Force we have something like 40 technicians who are well trained in the detection of small cracks, but they differ one from the other in their interpretation, so we have to be very careful that we do not ask them to find cracks which are so small that whilst one or two technicians are capable of finding the cracks, the others will fail. We must have confidence in the work that these inspectors are doing.

With regard to the remarks made by Mr Hope, I accept that designers today are designing for inspectability much better than they need to do. I must emphasise, however, that we also would like better inspectability in our old aircraft.

S.Hanagud (US)

I would like to ask a question regarding the UK paper, in which mention was made of acoustic emission. I would like to know what it is used for.

R.Dawson (UK)

I am sorry if Wing Commander Kent's paper has misled the questioner. We do not have any acoustic emission work going on in the Royal Air Force; what he was trying to indicate was that there is a need for research in this field. Perhaps our development teams will find something on the lines of acoustic emission to help us, so that while aircraft are in flight pilots may have an indication that there is a problem and be able to return to base in safety. In

particular, it would be useful to be able to detect the very tiny critical cracks which occur, for example, in welded structures.

T.Gaymann (GE – Session Chairman)

I am afraid I have a difference of opinion here and I think I should quote Dr Bolis' paper. If you have tiny cracks which you wish to watch during flight, then either the design is wrong or the wrong material has been used. This is not a problem for the NDI man, but a problem for the designer or the materials man.

R.Dawson (UK)

I agree entirely with our Chairman's remarks. We do not want this sort of structure in our aircraft, but unfortunately we seem to be getting it and we are very worried about it. Of course you can get into trouble if you use an aircraft in a different way to the role for which it was designed or if there is some design error, but I agree that the basic design should avoid problems of this nature.

D.E.W.Stone (UK)

I would like to say that whilst there may be no work on acoustic emission within the Royal Air Force, the British Ministry of Defence has a lot of activity in this field. Whilst I agree with the comments that application of acoustic emission to in-flight monitoring is a sign of desparation, I do feel that there is a considerable need for acoustic emission to be developed as a tool in materials testing and as a monitor in the structural strength test. We have still to solve the problem of detecting crack growth in the industrial environment, where electro-magnetic interference and the presence of other non-significant noise makes this very difficult.

D.M.Forney (US)

I would like to add my comment that I have doubts about the usefulness of structural monitoring during flight by acoustic emission. We have had a case in the USA where an aircraft was being monitored by this means, and was fitted with an indicator light in the cockpit. When the light went on, the pilot, who had apparently not been briefed very well, got so frightened that he crashed. On the other hand, in one of our large military aircraft we have four panels in the wing structure, any three of which can handle the load, thus providing a degree of redundancy. We would, however, like to know whether failure has occurred so that the crew can safely return to base. In cases like this, where we are listening for a very large bang, there might be some usefulness in monitoring, but when one is listening to very small cracks we have also concluded that there is too much other extraneous noise, and we have retreated into a long range research mode.

W.M.Imrie (UK)

My company specialises in the manufacture of aircraft landing gear. We are constantly looking for ways of reducing our costs by cutting down on NDI, and I wish to refer briefly to a method which we feel has been successful. It comes under the category of "method improvement" mentioned in one of Mr Forney's illustrations.

Many landing gears use very high tensile steel with a rather low fracture toughness; all these landing gears have to be subjected to etch inspection to check that there is no grinding abuse, which has a very disastrous effect.

It is common practice in both Europe and America to do this etching in nitric acid, which tends to "smut" due to the presence of carbides and other complex compounds, thus hiding the result of the grinding abuse. It is therefore necessary to scrub the part, which is expensive and time consuming. The process can be improved by diluting the nitric acid with alcohol, but for large parts the bath size makes the alcohol both expensive and dangerous as a fire risk. If water is used to dilute the nitric acid, hydrochloric acid etching is needed as a second etch to give sufficient contrast. This involves a further hazard of hydrogen embrittlement, and one has therefore to de-embrittle the part before it can be used.

Some time ago we looked for a compound which could be added to the nitric acid and would stop the "smutting" occurring. We believe we have been successful in this, and we have also cut out the necessity for hydrochloric acid and the consequent de-embrittlement process. We have thus evolved a process which is going to save us a lot of time and money and we have supplied this new compound to a landing gear manufacturer in America who is now evaluating it.

W.G.Heath (UK – Meeting Chairman)

I have been wondering about the more philosophical questions raised by the Rapporteur, the principal one being how can we bring the designer back into the loop? Perhaps at this point I ought to drop the mask of being the Chairman of this meeting and reveal myself in my true colours as a designer.

Recent events in the UK have caused designers to wonder what is wrong with the fail safe philosophy. In one case an aircraft was lost when a wing came off; in a second case an aircraft was lost when the tailplane came off; in a third case a whole fleet of aircraft has been grounded. All these incidents were due to the fact that cracks remained undetected for longer than the designer intended. The question designers have been asking is "How can we bring the inspector in the field into the loop? We have a fail safe philosphy which designers understand, which the airworthiness authorities understand, and which our NDI people within the Company understand. The man who doesn't appear to understand what we are trying to do is the inspector in the field. How can we bring him into the loop and make sure he understands what we want him to do, and also make sure he will go out and do it?"

The answer to that question has appeared at least in part in two of our papers today – those by Dr Bolis and Wing Commander Kent. The answer appears to be "Tell the inspector when and where he has to look". That is a very good answer to the question as far as it goes, but unfortunately it raises a further problem. Our experience has been (and I am sure that other peoples' experience is similar to our own) that if we point the inspector's nose too closely at where he must look he misses enormous defects quite nearby. If we say to him "We had a crack on the fatigue test specimen in bolt hole number 17 in row number 3; that's where you should look", he will look at bolt hole number 17 in row number 3 with great care. He will bring all his NDT equipment to bear on that hole and will pronounce it clean – but he will miss a yawning chasm at bolt hole number 18 in row number 3.

On reflection, I do not think we should talk about bringing designers into this loop or inspectors into that loop. Really we should be asking how can we bring all these people together so that we can tackle a very serious problem. We must be sure of finding cracks before an accident occurs and whilst they are still short enough to be repaired.

T.Gaymann (GE – Session Chairman)
One answer to this question is to improve the quality of the full scale fatigue test so that you don't get just one crack but a number of cracks. You then bring the NDI man along so that he can see the cracks and develop his methods as the full scale test proceeds.

R.T.Smith (US)
I cannot suggest how this problem might be solved, but I would like to draw your attention to the principle of privity, i.e. the relationship of a happening to the two bodies most directly involved. In the USA since 1960 the idea has slowly evolved that the operator and the passengers are not the only two bodies involved in an accident; more and more cases are arising where the designer is liable. One of the ways in which the designer can protect himself is to show that he has been aware of, and used, all the standards which are applicable, and these include a consideration of NDI.

A.R.Bond (UK)
I am the unfortunate person who ended up with the fleet on the ground, and I would like to point out something which shows that someone was paying attention to the very point that Mr Heath raised. An aircraft had a fuel leak, and the inspector who went to investigate saw a crack and called in the NDI man. Although these cracks were in secondary structure, the NDI man knew from his discussions with the manufacturers that these cracks were rather close to some bolts from which cracks had developed during the fatigue test. We therefore called in the manufacturers before we started checking the aircraft around this critical area, so that in this particular case it was the NDI man who called in the designer. It was not a case of the NDI man missing a crack because he had concentrated too closely on the place which the designer had defined.

R.Dawson (UK)
This sort of thing is happening to us in the Royal Air Force. I must emphasise that we train our men to keep their eyes open when we ask them to examine an aircraft. They may have nothing to do with structures – they may simply be changing a black box – but if they keep their eyes open they may well find a structural defect. Unfortunately the human eye isn't very efficient, particularly when you have paint and dirt and fluids around. We need NDI equipment to find a small crack, but unfortunately this equipment isn't in use as a search tool; unless we are talking about gross cracking, we cannot expect our technicians to find defects.

T.Gaymann (GE – Session Chairman)
There is a possibility of using the fleet leader, suitably fitted with laboratory type instrumentation, as a monitor.

R.Schutz (GE)
If you have finished a full scale fatigue test, you have 500 to 1000 different critical locations and much depends upon the skill of the NDI man in establishing when the cracks occurred and at what frequency they should be inspected in service.

W.G.Heath (UK – Meeting Chairman)
The problem is that the fatigue test can never accurately represent what is happening in service. This is particularly true with the civil market if an aircraft is sold to many different operators who operate them in a great variety of ways. It is also true in the military field when an aircraft is operated in a different role every day. In these cases you can never be sure which crack will appear first, and you must therefore inspect all the critical areas, and start inspecting as soon as possible. This is where the difficulty arises. If you ask the inspector in the field to inspect all the critical areas, we have the result which was described in Wing Commander Kent's paper – the man gets bored and tired and fails to do his job efficiently. If you narrow the field so that he has a limited area to inspect, he still misses the obvious. This is a great dilemma and I don't know how to solve it.

T.Gaymann (GE – Session Chairman)
If the use is different from the fatigue test (I assume that the fatigue test is a very detailed one) then you can measure the difference by flight fatigue meters and so on. Calculations can then be used to predict failures in service.

R.Mitchell (UK)

It is a very difficult problem and I don't really know the answer. I think that most of the defects we find in service can be traced back to designers who make mistakes in the detail design, and I would agree with Wing Commander Kent's contribution in this respect. One answer therefore is to improve the designers' capability. Although some of the cracks we find in service are predicted by the designer, I would suggest that the vast majority of cracks are not. Perhaps the designer can look at the structure and make a structural audit to predict the zones that need special inspection.

The other comment I would like to make is that the use of more exotic materials in each new generation of aircraft is a step in the wrong direction, and I believe that material selection is the real key to this problem.

M.Perry (UK)

We have heard a lot about minimum detectable size defects using various techniques, and I would like to refer back to the paper by Dr Antona. We are not interested in minimum detectable sizes of defect under idealised conditions; what we are interested in is a high confidence level of detecting the defect which is probably much larger than the minimum we can detect in the laboratory. I think the cases we have heard about 0.4 mm cracks being detectable by ultrasonics depend very critically on the way the instrument is handled, and I believe we have done a good job in misleading the designer during our discussions.

T.Gayman (GE – Session Chairman)

We have looked at two problems – firstly the inspection of aircraft in service, and secondly the problem of aircraft design where one needs to avoid making errors, but at the same time needs to introduce new materials, new processes and new philosophies. I think that when considering a new aircraft project, the NDI man should be consulted by the designer at the earliest possible stage, modifying the basic layout if necessary.

APPLICATION OF SMALL-ANGLE NEUTRON SCATTERING TO NDI OF MATERIALS AND MANUFACTURED COMPONENTS

by

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1. INTRODUCTION

The small-angle scattering technique has been used for many years xith X-rays at a wavelength of about 1 Å. Many important results have been achieved with this technique, like e.g. the Guinier-Preston zones in aluminium-copper alloys /1/.

The use of neutrons, instead of X-rays, in the more recent years, allows to overcome two of the greatest difficulties arising from x-rays, that is :

- to measure large thicknesses of materials
- to avoid multiple Bragg scattering from policristalline materials by using wavelengths $\lambda > 2d_{max}$ with d_{max} the maximum interplanar cristalline spacing /2/.

On the other hand, the use of neutrons has the great disadvantage of the low neutron intensities usually available from reactors in the wavelength region $5 < \lambda < 20$ Å.

To overcome this difficulty, cold sources, guide neutron tubes and multidetector systems have been designed and used with research reactors /3/.

The FIAT device for small-angle neutron scattering (S.A.N.S.) measurements is shown in fig. 1 /4/.

The cold source gives a gain for long - wavelength neutron intensity depending on the type and temperature of the moderating material (liquid propane in the present case).

The guide tube leads neutrons away from the reactor in a zone with low background and performs a preliminary wavelength selection.

The mechanical wavelength selector perform the desired selection with a wavalength resolution usually of the order of 10%.

The detection system is given by a multicellular bidimensional BF_3 detector that fournish the planar neutron scattered distribution in a plane perpendicular to the neutron beam axis as schematized in fig. 2.

The cold neutron fluxes obtainable with a usual swimming-pool reactor operatings at a power of 5 MW is of the order of 10^4 cm^{-2} sec^{-1} on the sample, that is, at the D2 slit in fig. 2.

The relatively new technique is a very useful tool to explore inhomogenities in materials ranging, from about 30 Å to 10^5 Å. This large interval of detectable dimensions allows to have N.D. informations in a very large fiel of applications, like :

- phases transformations and evolution in steels, nichel superalloys, aluminium alloys after thermal treatments /5,6/;
- degradation phenomena in materials as consequence of fatigue, creep or cold work /7/;
- microvoids in ceramics /8/;
- radiation damage effects /9/;
- macromecules structure in biology /10/.

This picture is probably incomplete but sufficient to demonstrate the importance of the SANS technique both in solid state physics, in metallurgy, biology and engineering problems.

With the use of high neutron flux reactors /11/ this technique has been improved for fundamental researchs: more recently has been demonstrated the applicability of the SANS to technological problems by using only research reactors at lower powers /4,5,6/. In future, with the developement of others neutron sources like e.g. accelerators or plasma focus the developement of this technique will be probably improved and used more extensively.

In this paper we will summarize, after a brief mention of the theoretical background, the most important results obtained with a certain number of materials submitted at different treatments.

Then, this paper will be essentially, divided in two parts :

a) short examples of scattering from dislocations, voids or particles and magnetic domains;

b) applications to technological problems like microstructural evolution of turbine

blades and in general to nichel superalloys after operation and correlations with new design criteria.

2. THEORY AND EXAMPLES

A collimated beam of "cold neutrons" (wavelength $\lambda > 5$ Å) impinging on a material characterized by local fluctuations $\Delta\eta$ of the scattering length density η ($\eta = bN$ with b = nuclear + magnetic scattering length and N = atomic density) gives rise essentially at two different phenomena :

- refraction and partial reflections from large inhomogeneities (usually from centers of the order of some μm)
- diffraction from small centers (usually from 30 Å to some10^3 Å).

These phenomena are well defined by the phase difference ϕ between the phase change in traveling the inhomogeneities and the same phase change in vacuum.

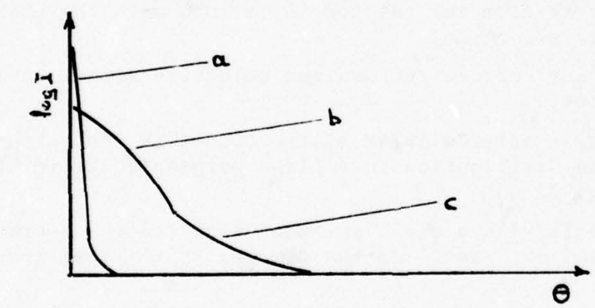
If $\phi \ll 1$ the diffraction theory is valid, if $\phi \gg 1$ the refraction theory holds and the direct beam is broadened by multiple refraction /12/.

The phase change is given by :

$$\phi = \Delta\eta . \lambda . l \quad (1)$$

where λ is the neutron wavelength and l the scattering center dimension.

From a qualitative point of view the following figure gives the visualisation of the two phenomena of refraction and diffraction superimposed.



Refraction and diffraction

a) direct beam
b) broadened beam
c) diffracted beam
θ = scattering angle
I = neutron intensity

In the case of multiple refraction only, the particles or inhomogeneities are assumed to scatter indipendently and this gives rise approssimatively to a gaussian distribution of the scattered neutron intensity. If we assume the beam full width $\Delta\theta$ at half-maximum as characteristic parameter of the beam broadening, we have :

$$(\Delta\theta)^2 - (\Delta\theta_o)^2 = \alpha n \left[\frac{\Delta\eta\, \lambda^2}{2\eta}\right]^2 \left[\beta + \ln \frac{\gamma}{\Delta\eta\, \lambda^2}\right] \quad (2)$$

where : α, β, γ constants depending on slit geometry and scattering inhomogeneities shape

n = number of refractions

$\Delta\theta_o$ = direct beam broadening

In the case of diffraction only, we can introduce in a general way the scattered intensity or the differential scattering cross-section $d\Sigma/d\Omega$ as follows :

$$\frac{d\Sigma}{d\Omega} = \left| \int_V \eta(\bar{r}) \exp(i\, \bar{k}\, \bar{r})\, dr \right|^2 \quad (3)$$

where : $d\Sigma/d\Omega$ = differential scattering cross section

$\eta(\bar{r})$ = density scattering length characteristic of the shape and type of the scattering center

$|\bar{k}|$ = scattering vector $\simeq \frac{2\pi\theta}{\lambda}$

θ = scattering angle

λ = neutron wavelength

For the most common shapes of the scattering centers, that is spheres, discs, cylinders etc. and for linear dislocations or random particles the typical scattering functions are well known /13/.

It is importan to point out the different asympotic value of the scattering function or scattering cross-section slope for different centers. Thus this fact allows to discriminate between different scattering centers /6/.

2.1 THERMAL TREATMENTS

Particles or voids have the same scattering function; in the most general case, particles have a certain polidispersion of dimensions N (R) and the differential scattering cross-section $d\Sigma/d\Omega$ is given by :

$$\frac{d\Sigma}{d\Omega} = \Delta\eta^2 \int N\ (R)\ F^2\ (KR)\ dR \qquad (4)$$

where $\Delta\eta$ is the scattering density length

F(KR) the particle scattering function depending on the shape of the particle.

In the particular case of spherical particles of radius R it is possible to evaluate N (R) from the relation (4 by using the Mellin transforms and supposing that the asymptotic behaviour of the scattering function follows the Porod law for three dimensional scattering centers /14/.

A particle scattering examples is given by the scattering from an aluminium alloy (Avional 14) in wich the structure is given by a f.c.c. austenitic matrix where are uniformly distributed thin disks of Cu-Al precipitates that evolves from the G.P. zones θ' to the θ stable phases.

The effect of aging treatment on Avional 14 is clearly measurable by SANS as rapresented in fig. 3, where is shown the evolution of the scattered intensity against the scattering angle at different times and at an aging temperature T = 175°C for a specimen of about 7 cm of thickness /15/.

The curves evolution allows to establish what follows :

a) in the aluminium alloy it is present a stable fraction of large inclusions, not sensitive to aging treatments (low scattering angle);

b) during ageing there is a large increase of bi-dimensional precipitates, probably discs, whose growing law follows approximatly the Lifshitz-Wagner theory.
The presence of bi-dimensional scattering centers is given by the tendency of the asymptotic law to have a -2 slope.
Transmission, electron microscopy has confirmed the SANS measurements.

As a second example of thermal treatment effects, the evolution of austenite in the maraging steel 17-4PH after different tempering treatments will be given * /6/.

The microstructure of the 17-4PH steel is complex and is greatly influenced by termal treatments. After tempering it is possible to have inside a martensitic structure a certain fraction of austenite and small precipitates. The superposition of multiple refraction from magnetic domains or austenite and diffraction from small precipitates represent a great difficulty to the understanding of the scattering curves. The application of a magnetic field during the measurements allows to eliminate the magnetic domain effect.

Therefore SANS measurements have been performed on the heat treated samples in the following conditions :

- without the magnetic field across the sample
- with the magnetic field near saturation as is schematized in fig. 4, to orientate all domains in the same direction and to eliminate multiple refraction effects.

a) Without the magnetic field, the direct beam broadening measured for variuos samples, treated at different tempering temperatures, is given in fig. 5 and compared with X-rays measurements.

* Work performed under CEE contract.

The diffraction effect clearly influences the beam broadening expecially at high tempering temperatures.

b) With the application of a magnetic field the scattering curves are modified as shown in fig. 6 for 200 and 600°C of tempering temperatures. In this case the beam broadening for water quenched steel become quite similar to that obtained with X-rays as is shown in fig. 7. The most important difference is that with X--rays austenite is measured only in surface, on the contrary with SANS one obtain an average "bulk" value. In the present case the thickness of the specimen is 7 mm.

2.2 COLD WORK

The "cold work" effects on pure copper have been measured by SANS. The specimen of pure copper has been treated as follows :

a) plastically deformed up to $\Delta L/L = 0{,}3$ of elongation

b) annealed at 300°C under vacuum

c) annealed at 350°C under vacuum

The scattering curves for cases a, b, c are shown in fig. 8; from these scattering curves is clearly visible the effect of defects recovery after annealing. The type of defects present is not well defined from the slope of the scattering curves, probably due to the scattering superposition of dislocations and microvoids presents after "cold work".

2.3 CREEP *

The effects of creep on Alloy 800 are given as one example of microvoids evolution measured by SANS on samples submitted at different stresses and temperatures.

The measurements have been performed both along the axis of the sample and in function of creep time at temperatures of 700 and 760°C. The measured quantities are the correlation length l_c, that is a quantity proportional to the average dimensions of microvoids /6/, and the density variations.

An example of the correlation length evolution during creep for an applied stress of 6 kg/mm^2 at a temperature of 760°C, measured at about 4 mm from rupture, is given in fig. 9.

In this figure is clearly visible the initial increase due only to thermal effects and the growing of microvoids up to rupture. The density variations measured by SANS in this case are of the order of $10^{-4} \div 10^{-3}$, in comparison with those obtained with density measurements by means of the "balance method" as shown in fig. 10. These results are in good agreement if we consider that the measured volume with neutrons is in a zone between 3 and 7 mm from failure.

Due to the sensitivity of the method it is then possible to detect the residual life of the material by considering that all the specimen will be broken when the density changes are about 10^{-2} /16/.

3. TECHNOLOGICAL APPLICATIONS

The small angle neutron scattering technique is particularly suitable to examine microstructural degradation phenomena in nichel superalloys.

The examined phenomena in these type of alloys are :

- thermal treatments
- creep and thermal fatique in turbine blades

The examined alloys are :

- Inconel X-750
- Udimet 520
- Inconel 700
- In 100

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* Work performed under CEE contract

The N.D. examination carried out allows to determine γ' dimensions and concentration, microvoids and degradation phenomena after service.

In some cases the SANS results have been compared with transmissions electron microscopy measurements.

3.1 INCONEL X-750, UDIMET 520 NICHEL SUPERALLOYS

Thermal treatment effects on microstructures of nichel superalloys Inconel X-750 and Udimet 520 have been evaluated by SANS.

Complete and partial aging treatments of Inconel X-750 alloy are compared by the scattering curves shown in fig. 11. From this type of measurements the concentration and average dimensions after different aging times have been deduced; the results are summarized in fig. 12 and fig. 13 respectively. In the same figures are also reported the destructive γ' results obtained by electrochemical dissolution and T.E.M. The thicknesses of the examined samples is of about 4 mm.

Similar measurements have been performed on Udimet 520 after solubilization and aging treatments. The scattering curves are shown in fig. 14 where, by comparison, in also reported the T.E.M. on the Udimet 520 after complete aging treatments. From these scattering curves it is remarkable to point out the interference effects arising from high γ' density. From the position of the maximum it is also possible to measure the average distance of the scattering centers.

3.2 INCONEL 700 TURBINE BLADES

The evolution of γ' phase along the axis of the blades has been measured at different operating times and conditions.

The examined material is an Inconel 700 nichel superalloy submitted to different conditions of normal or overtemperature /7/. The relative results have been shown in fig. 15 where it is possible to point out the large increase of γ' phase radius in the middle of the blades after $\sim$ 910 h or for overtemperature effects at lower operating times.

This microstructural degeneration process is directly correlated with the possibility to deduce residual life of the aircraft blades.

3.3 IN 100 TURBINE BLADES

The γ' concentration and dimensions have been evaluated for In 100 turbine blades during about 312 h of operation in gas turbine. An example of scattering curves for blades after 0 hr and 312 h of operation are given in fig. 16. In this fig. it is also shown the transmission electron microscopy measurements (T.E.M.). From the T.E.M. and SANS results it is possible to deduce the presence of a primary γ' phase of large dimensions and the effect of thesmaller secondary γ' phase in the new blades. In this case small degeneration effects have been observed up to 312 h.

The relative γ' concentration and average dimensions are shown in fig. 17. From this fig. it is possible to observe a certain γ' concentration fluctuations arising essentially from differences in the microstructure of the blades /17/.

3.4 FIBRE COMPOSITES

All the reported neutron effects are connected with isotropic scattering from randomly distributed centers. An example of anisotropy in the scattering is given from carbon fibre composites. The examined composite is a carbon-carbon fibres composite measured in two different orientations with respect to the neutron beam axis. In one case (fig.18) the measurements have been performed with the fibers parallel to the slit as reported in fig. 2; in the second case the fibers are oriented in a normal position with respect to the first case. The large anisotropy of the scattering has not been completely interpreted but it seems to be due to microvoids between the fibers and the matrix. Others measurements at different wavelengths are necessary to correlate the large scattering effects to the microstructure.

4. CONCLUSIONS

The examined examples of the application of the small-angle neutron scattering technique to practical problems allow us to conclude what follows :

- the possibility to detect in N.D. way inhomogeneities ranging from 30 Å to $\sim 10^4$ Å like precipitates, microvoids, dislocations is well established;
- the evaluation of the residual life for materials after creep, thermal fatigue or others degeneration processes is possible after correlations between properties and microstructure evolution;
- the increase in the knowledge of the microstructure degeneration before rupture is very important to increase the reliability of the ND control and allows to decrease the "safety factors" usually used for the design of particular components;
- the possibility to follow the microstructural degradation of materials during service allows to define a programme for the "regeneration" of components of high costs like turbine blades or similar components.

The increasing development of new neutron sources different from research reactors will give the possibility to apply more extensively this N.D. technique of examination.

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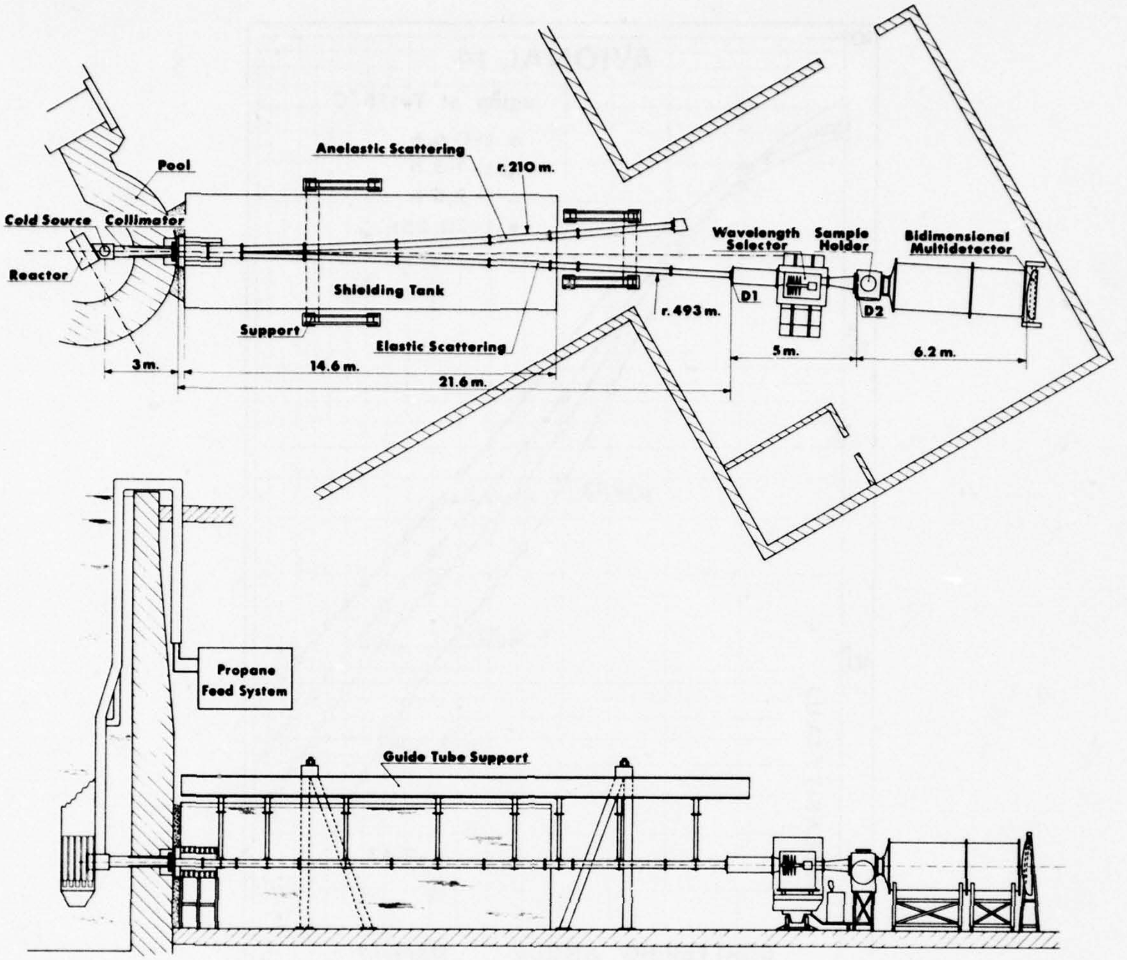

Fig.1 Small angle neutron scattering device

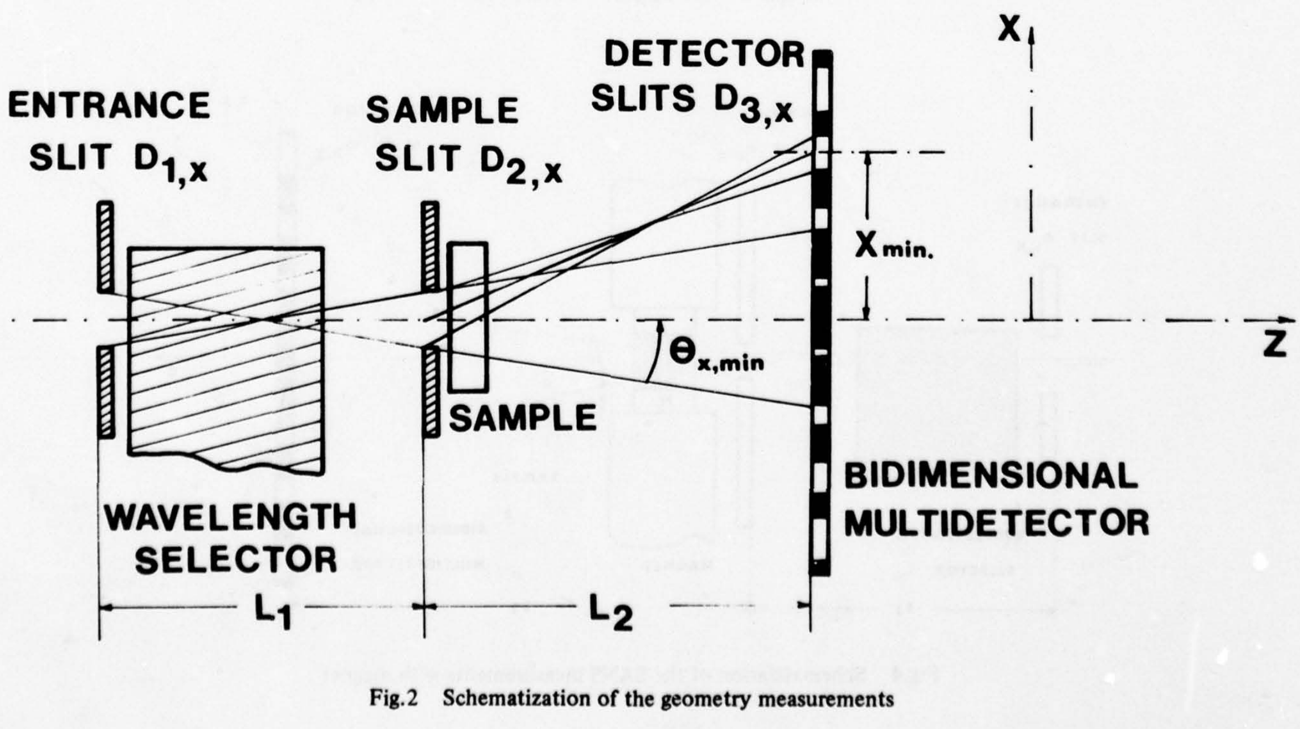

Fig.2 Schematization of the geometry measurements

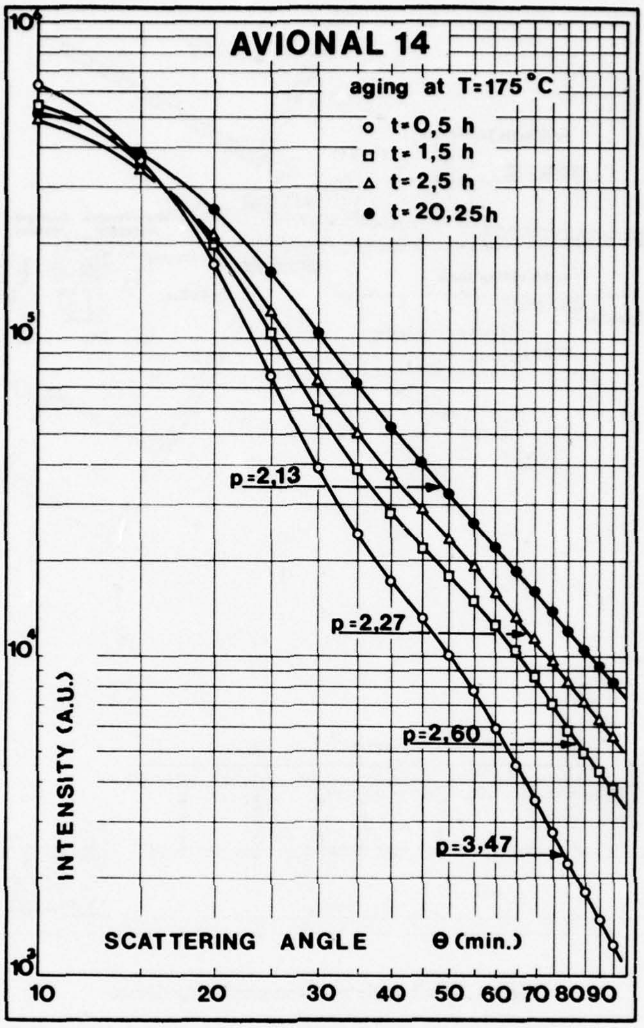

Fig.3 Scattering from Avional 14

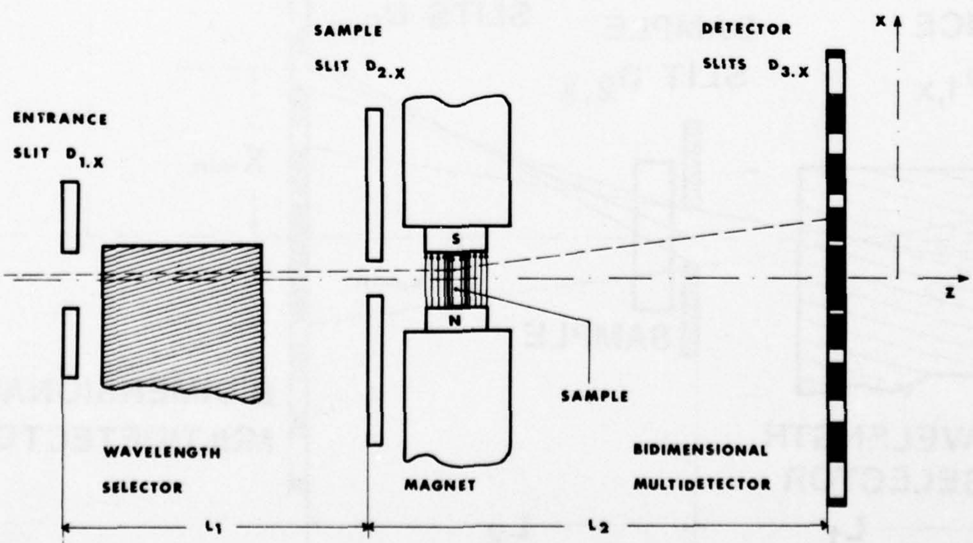

Fig.4 Schematization of the SANS measurements with magnet

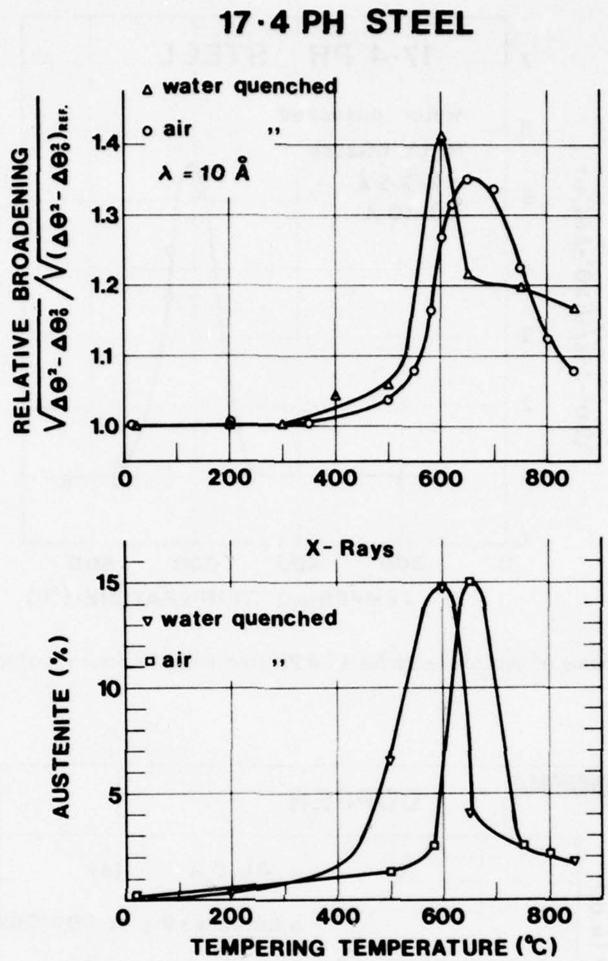

Fig.5 Broadening of direct beam for 17-4 PH steel at different tempering temperatures

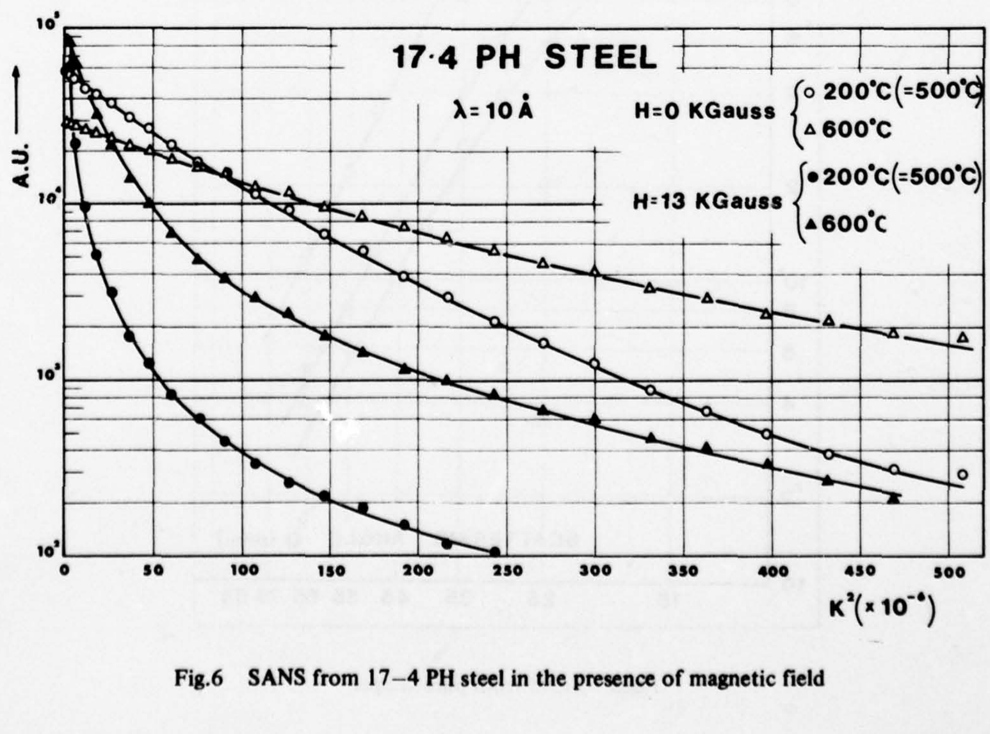

Fig.6 SANS from 17–4 PH steel in the presence of magnetic field

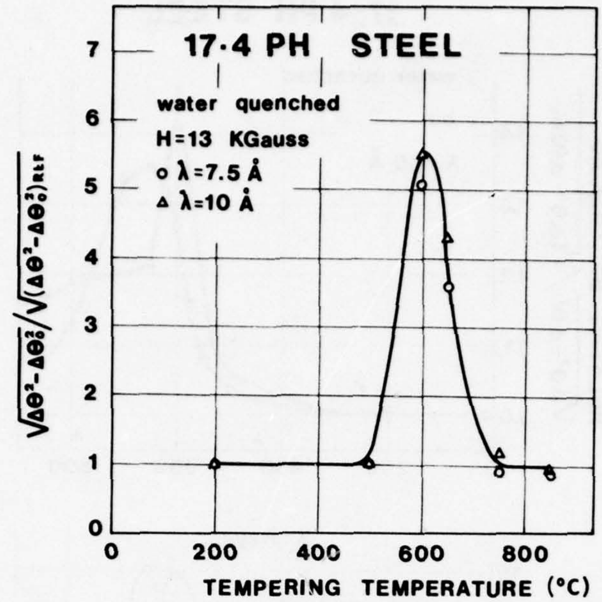

Fig.7 Broadening of neutron beam for 17-4 PH steel with the presence of magnetic field

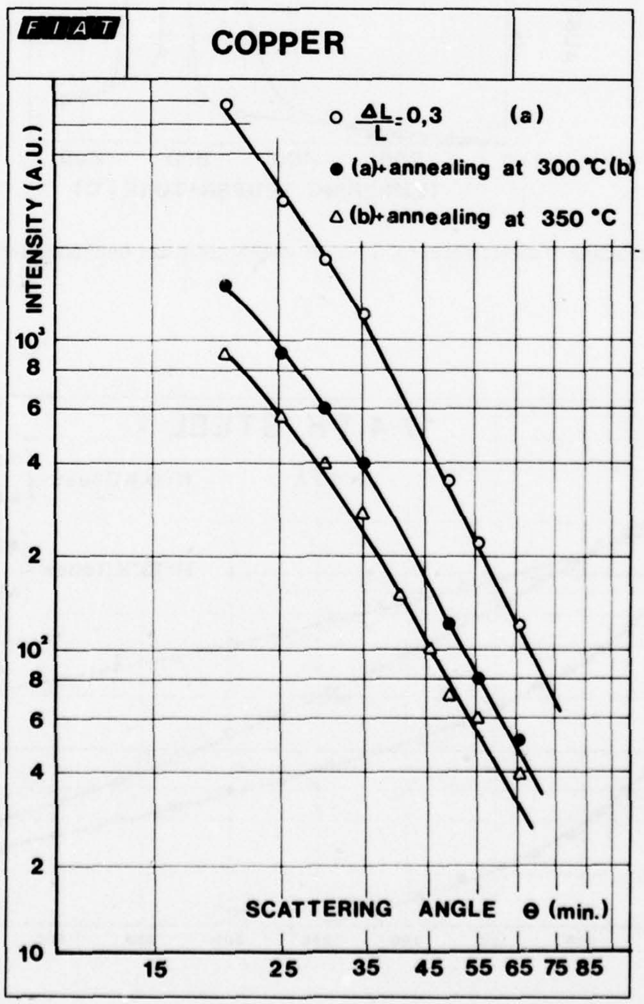

Fig.8 SANS from pure copper

ALLOY 800 - CREEP

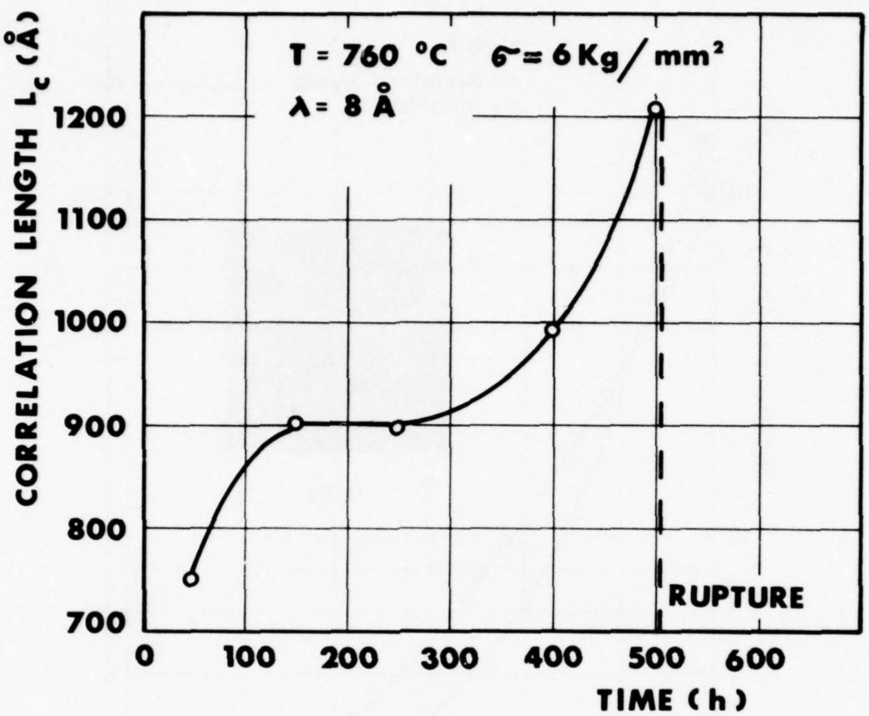

Fig.9 Correlation length evolution l_c for alloy 800 during creep

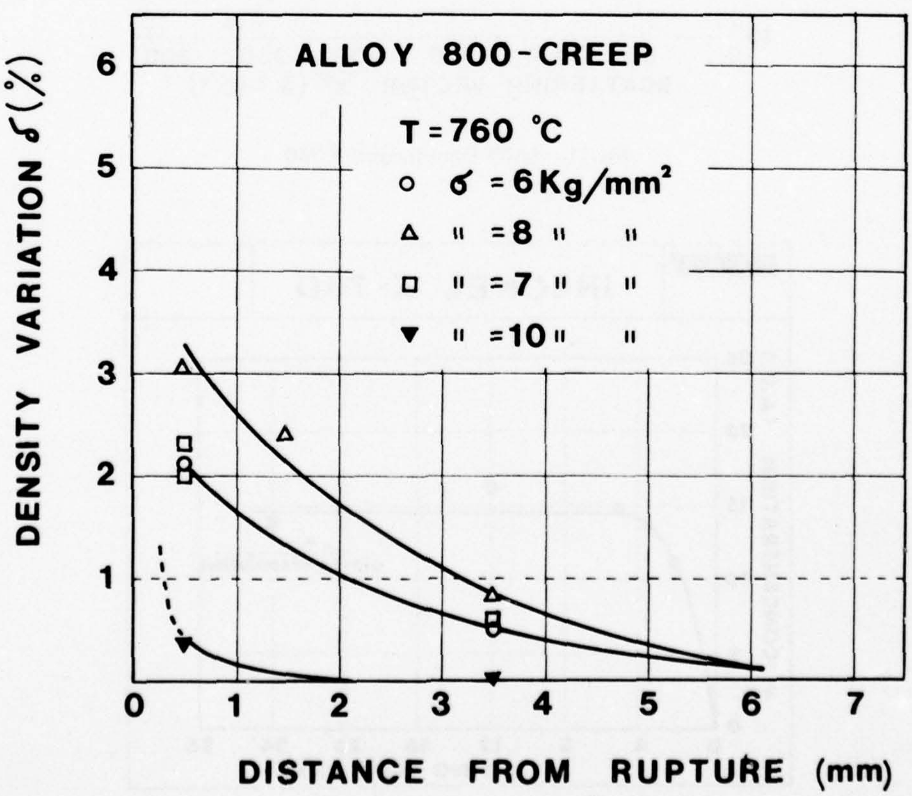

Fig.10 Density measurements for alloy 800

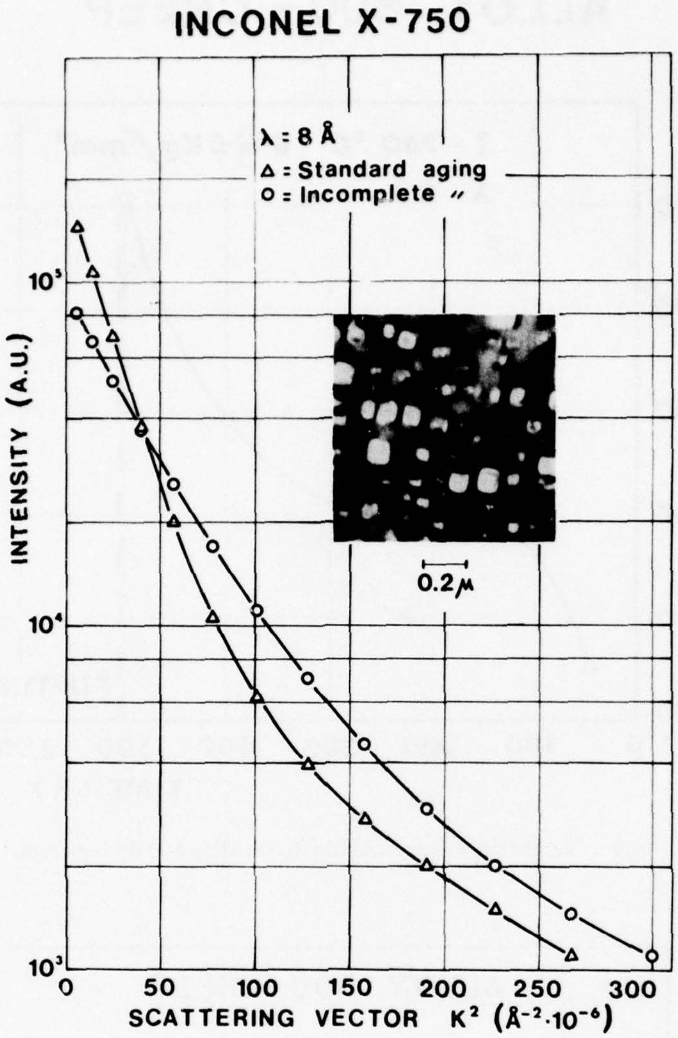

Fig.11 SANS from Inconel X-750

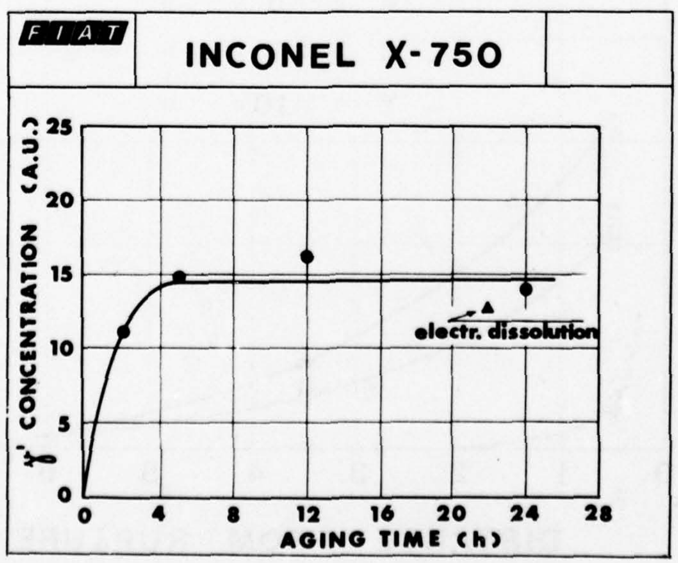

Fig.12 Concentration of γ' vs ageing temperature

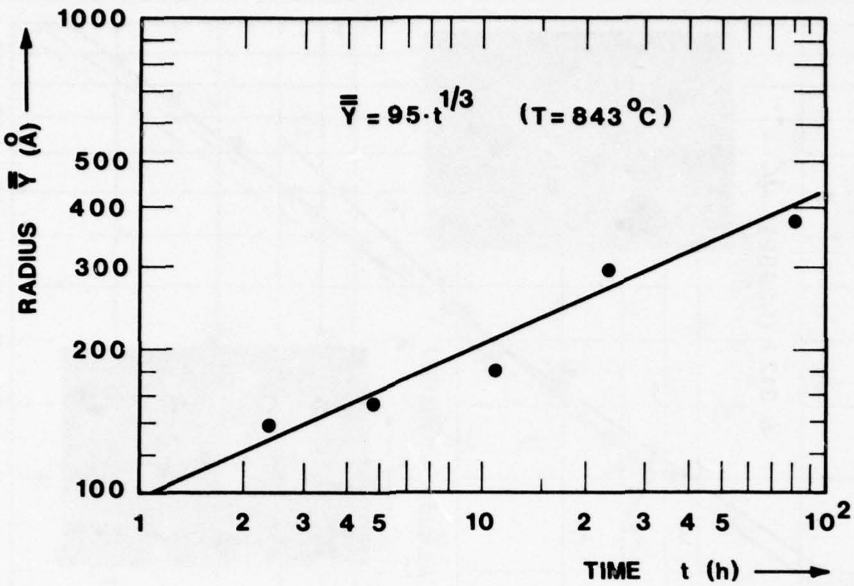

Fig.13 Average dimension evolution of γ' particles

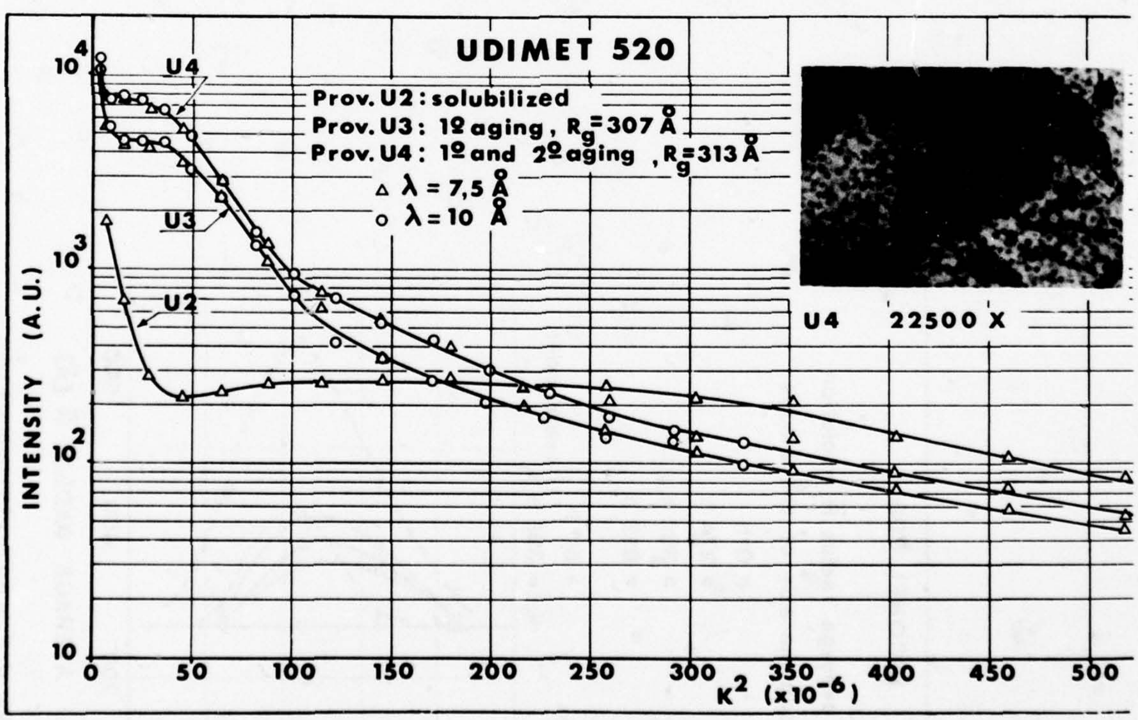

Fig.14 SANS from Udimet 520

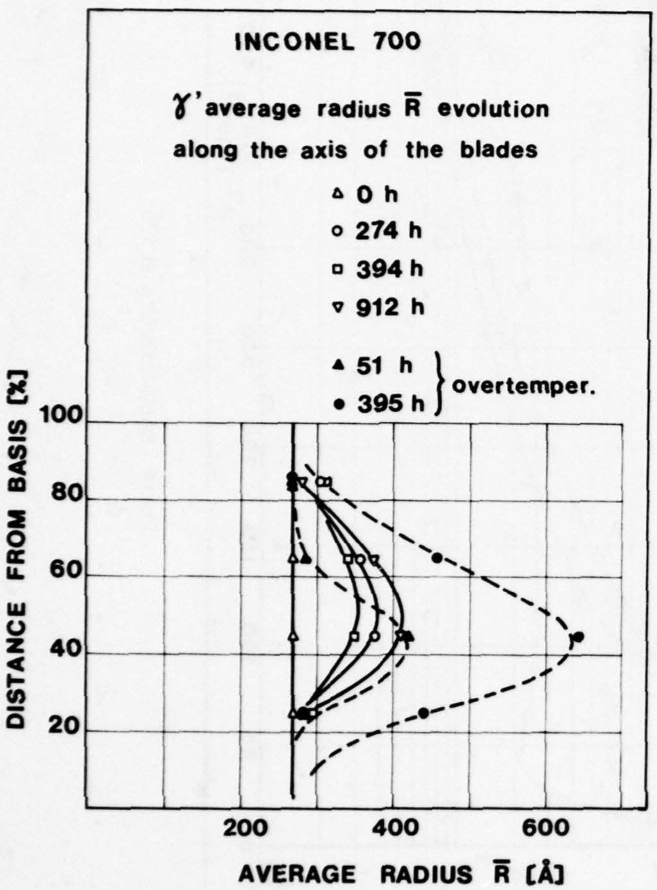

Fig.15 Evolution of γ' in Inconel 700 turbine blades

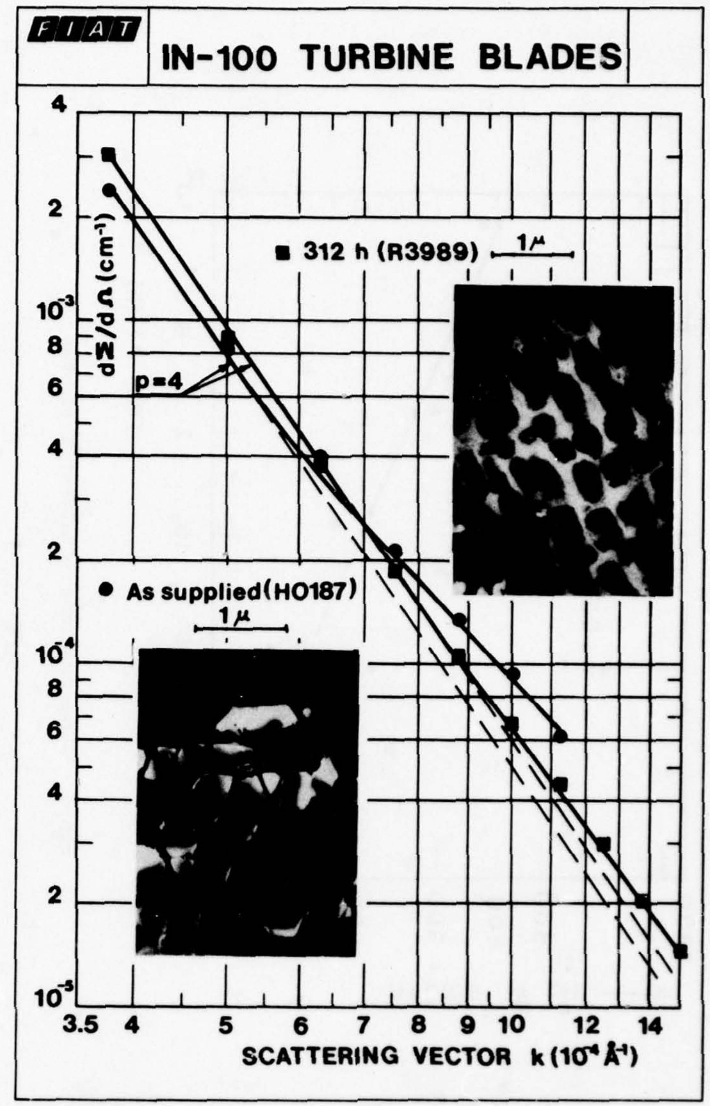

Fig.16 SANS from In 100 turbine blades

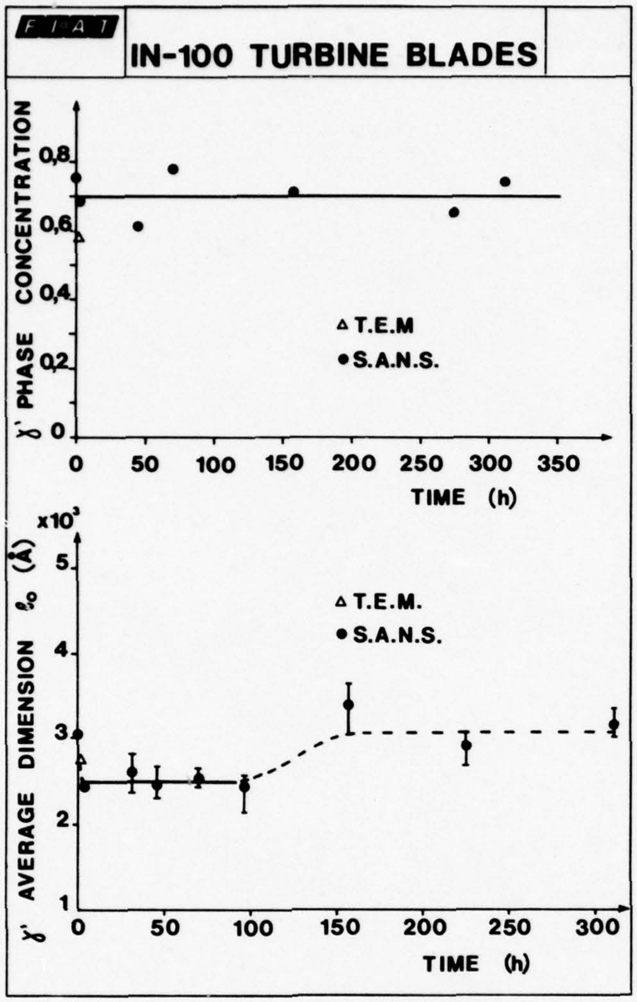

Fig.17 Evolution of γ' concentration and dimension for In 100 turbine blades

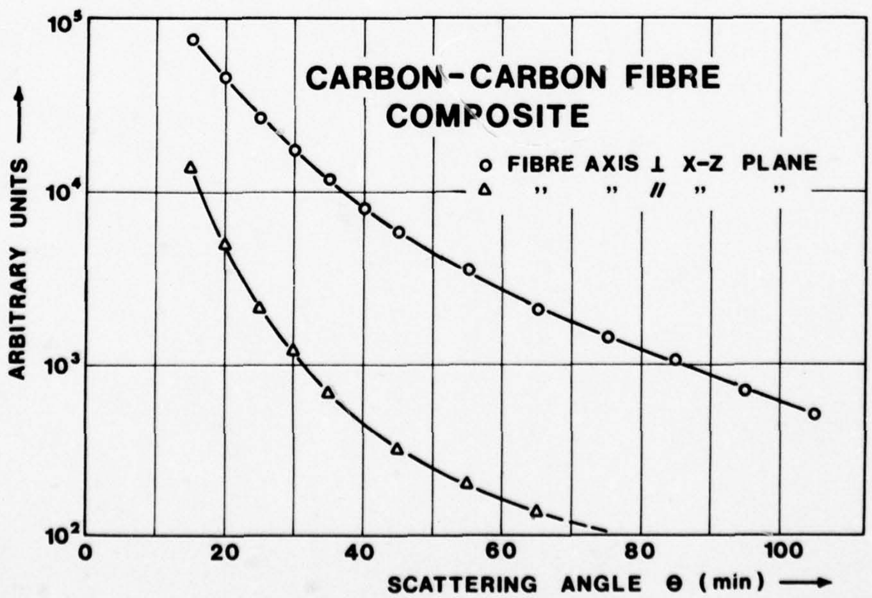

Fig.18 SANS from carbon-carbon composites

SURFACE CORROSION EVALUATION BY RELATIVE MAGNETIC SUSCEPTIBILITY MEASUREMENTS

by

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1. INTRODUCTION

One of the important requirements for the operational behaviour of high temperature components is the corrosion resistance of the involved materials.

The increasing severity of service conditions, especially concerning temperature, not only stimulates material development for achieving further quality improvements of superalloys and stainless steels, but also calls for additional or improved methods of non destructive testing.

Such methods should not only be useful for detecting the large defects which would rapidly cause component failure, but should be sensitive enough to localize corrosion effects in the very early stage of the degeneration process. They should in this way, besides of their role in quality control, be useful at the same time for studying the corrosion phenomena.

For this scope, a rather simple method of complementary character is proposed, which seems to offer rather wide promises.

The method is based on the well known principles of a magnetic balance /1/.

It utilizes the fact that superalloys and stainless steels change their magnetic susceptibility during oxidation and carburization in their subsurface layer.

Selective diffusion and reaction does infact influence there the ratio of ferromagnetic (Fe, Co, Ni) and non ferromagnetic (e.g.: Cr) elements constituting the solid solution alloy matrix.

The sensitivity of the method is on one hand based on the large variations of magnetic susceptibility obtained by relatively small local compositional changes and on the possibility to measure very small attractive forces on the other.

Its simplicity is due to the fact that it works at zero frequency and depends on magnetic susceptibility only, whilst the more conventionally used inductive coil techniques additionally depend on the electrical conductivity of the material and on the used frequency.

As additional facts, which seem to be promising for not yet explored applications, one may mention the susceptibility dependence on temperature and on structure. One might obtain in the future from a susceptibility - temperature curve, information on the composition of the alloy matrix and on the nature of secondary phases.

The present note reports on the information principle of the method and on measurements performed in IN-100 aircraft turbine blades, in INCONEL X-750 power station turbine blades and in INCONEL X-750 creep samples.

2. THE INFORMATION PRINCIPLE

As a consequence of selective oxidation at high temperature, three typical zones are present in a IN-100 turbine blade during service as shown in fig. 1: the oxide scale, the intermediate subsurface layer and the bulk.

Fig. 2 gives the corresponding concentration profiles of the compositional elements. It is seen that especially Co concentrates in the subsurface zone and gives rise to the increase of magnetic susceptibility.

In the INCONEL X-750 the situation is somewhat different. According to fig. 3 the concentration profiles in a (∿ 1000 h, 733°C) creep sample indicate that the susceptibility increase is mainly due to a decrease in Cr-concentration.

Magnetic susceptibility variations due to increments of the concentration ratio of ferromagnetic to non ferromagnetic elements are conveniently measured with a device as schematically shown in fig. 4. The device is composed by a small permanent magnet, mounted by means of a connecting rod on the sensible part of an extensometer cell. A variable distance piece defines the sensibility range by the working distance. A digital millivoltmeter, connected with the extensometer cell, gives the signal in terms of the attractive force F_z perpendicular to the surface.

The single force contribution dF_z from a single sample volume element dv, influenced by the field H of the magnet, is described by

$$dF_z = \frac{1}{2} \cdot \chi \cdot \frac{\partial H^2}{\partial Z} \, dv \tag{1}$$

where : χ = susceptibility

3. APPLICATION EXAMPLES

Routine measurements presently being performed at FIAT with the above described technique, mainly concern aircraft turbine blades of IN-100 and power plant gas turbine blades of INCONEL X-750, UDIMET 710 and similar materials.

Useful results have also been obtained during corrosion creep measurements in Co-superalloys, alloy 800 and AISI 316.

As examples, some results on IN-100 and INCONEL X-750 are reported.

3.1 COOLING CHANNEL OXIDATION OF IN-100 BLADES

In aircraft turbine blades a major problem is to control the inaccessible inner blade surface of the cooling channel where it is more difficult to apply protective coatings and where visual inspection is impossible.

Fig. 5 shows a typical oxidation of the cooling channel after 300 h.

In this case, the outer blade surface had been aluminized and showed little corrosion. The observation, that maximum oxidation of the inner surface occured at the tip of the blade, could be attributed to the fact that the cooling channel had been tapped near the root.

Further examples are given in fig. 6, where the signal (proportional to the susceptibility), measured along the blade axis, is reported for three typical cases :

- without any cooling channel (and without surface protection)
- with open cooling channel
- with tapped cooling channel.

It is interesting to note, that blades without internal cooling show maximum oxidation (external) in the middle; the ones with open cooling channels show their maximum at the bottom near the root, and the ones with the channel closed at the bottom oxidize more rapidly at the tip.

It is evident of course that these different internal oxidation profiles are due to combined effects of temperature, gas flow and load.

An atypical case of local corrosion attack at the inner cooling channel surface is demonstrated in fig. 7. An X-ray radiograph clearly confirms the indication of the magnometer device and localized the oxidation induced defect.

In typical practical cases of monitoring turbine blade corrosion in the cooling channel, it is more important to obtain the remaining unaffected bulk thickness rather than the thickness of the corrosion affected subsurface zone to which the magnometer is directly sensitive.

The initial bulk thickness is infact not the same in all blades and therefore not well known in the moment of corrosion control.

The problem can be resolved by combining magnetometer monitoring with an ultrasonic determination of the total blade thickness, which is the sum of bulk, subsurface, and oxide scale thicknesses. Fig. 8 gives the respective calibration curves for IN-100 turbine blades having internal cooling channel corrosion. The bulk thickness had been determined in these curves by metallographic sectioning. Such curves are now being used for non destructive determination of the bulk thickness after measuring the total thickness by ultrasonics and the corrosion effect with the magnetometer.

3.2 SURFACE OXIDATION OF INCONEL X-750

Magnetic measurements have become useful in creep-corrosion experiments where they allow to correlate sample fracture with proceeding oxidation.

As an example, fig. 9 shows how the magnetic susceptibility (magnetic force) develops along the sample axis with increasing creep time.

It is seen that a maximum is developed at a certain position along the sample axis. This maximum is located at the maximum strain position of the sample and indicates the place of most probable sample rupture.

The typical evolution of creep in air of INCONEL X-750 is demonstrated in fig. 10 for three different loads and for the case without load.

A steep increase of magnetic susceptibility is apparent at about 50% of the rupture time and might be used to monitor for failure approach.

The case of the sample without load is of course dependent on thermal stresses, generated any time when the sample was withdrawn from the furnace for measurement. The correlation of magnetometer response with sample rupture can be interpreted by crack formation. A crack infact exposes more surface to oxidation and locally developes more material with increased magnetic susceptibility. This is shown in fig. 11, in the case of an INCONEL X-750 power station turbine blade having 65000 h of service time.

ACKNOWLEDGEMENTS

The contributions of P. Pizzi, G. Calcagno and A. Rastaldo to this work are greatfully acknowledged.

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/1/ E. Passaglia (Editor) "Measurement of Physical Properties" Part 2. Vol. VI. John Wiley & Sons.

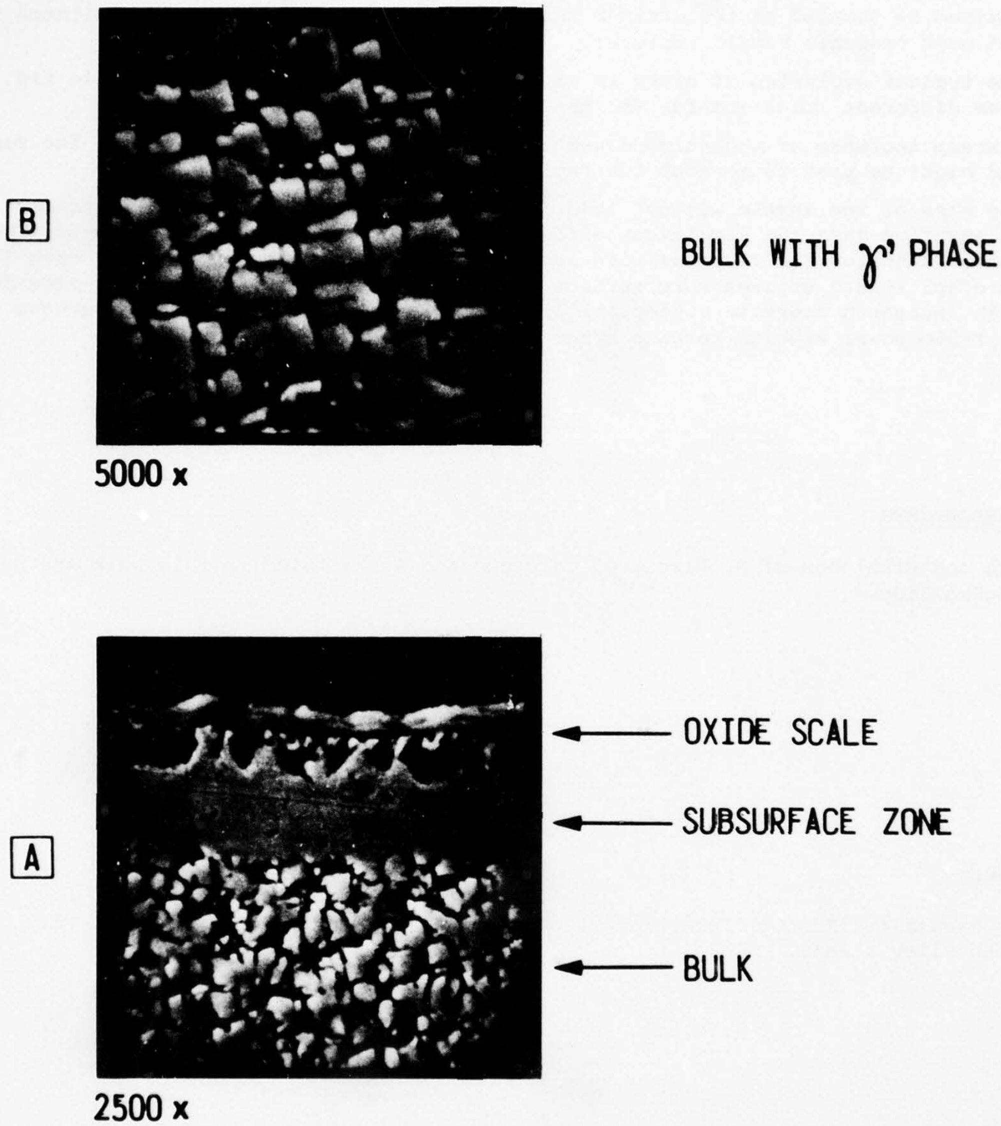

Fig.1 Formation of the typical subsurface zone in an In-100 turbine blade after 300h service

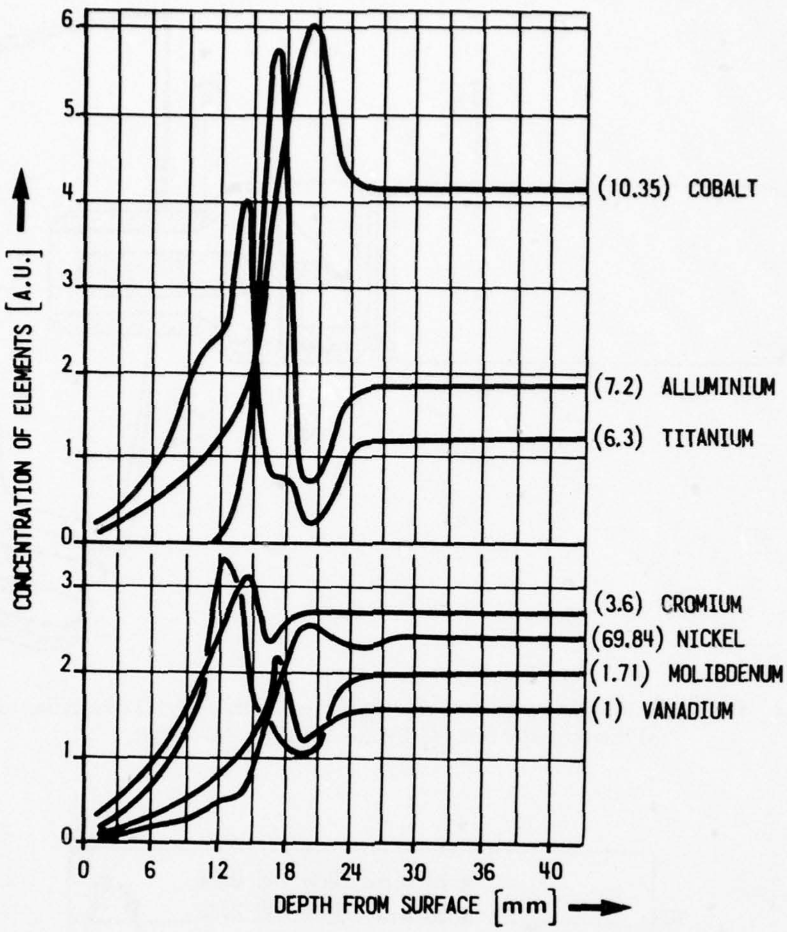

Fig.2 Concentration profile at the surface of an In-100 turbine blade after 300 h service

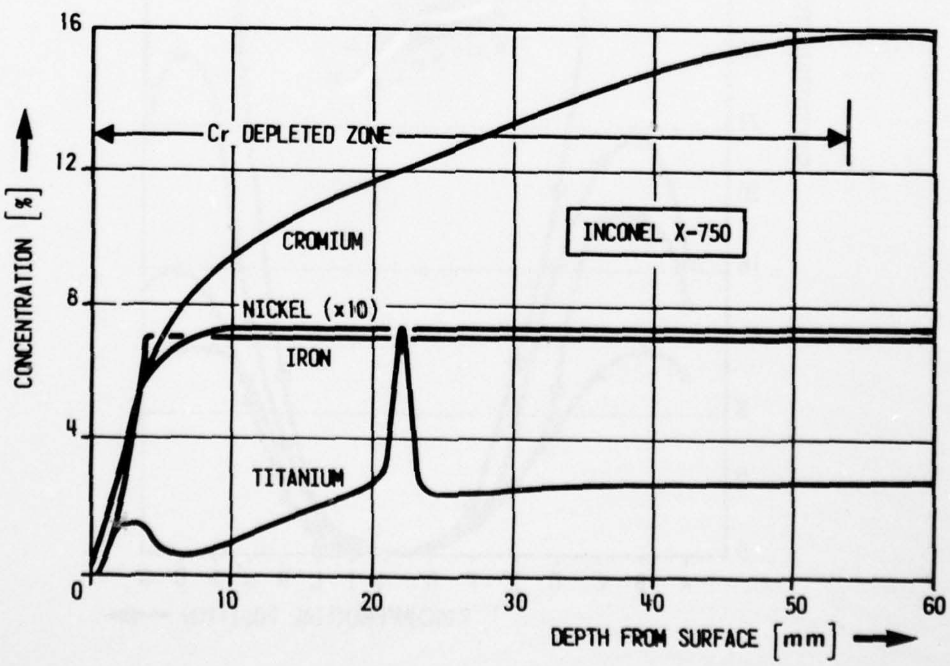

Fig.3 Concentration profile of a creep sample (1000h, 733°C)

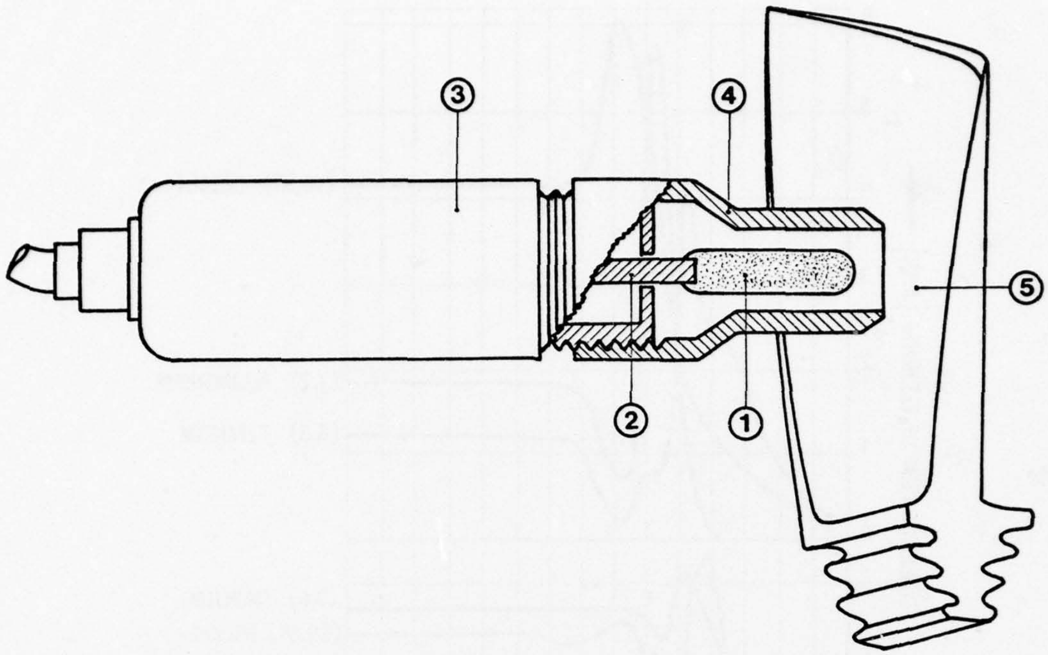

Fig.4 Measurement devices composed of: (1) permanent magnet, (2) connecting rod, (3) extensometer cell, (4) distance regulater, (5) sample

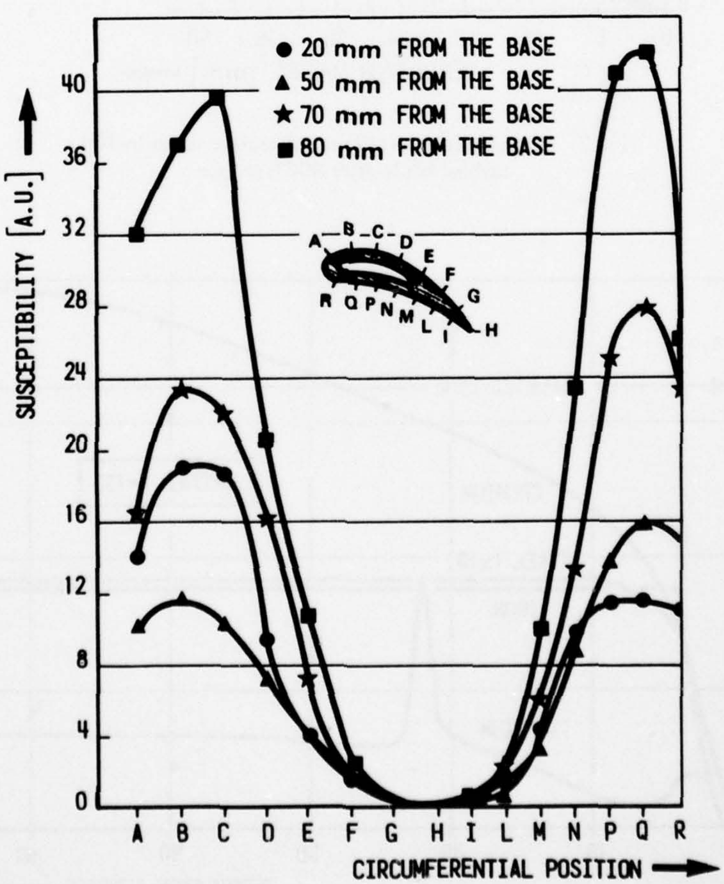

Fig.5 Oxidation in the internal cooling channel of an In-100 aircraft turbine blade (312h service)

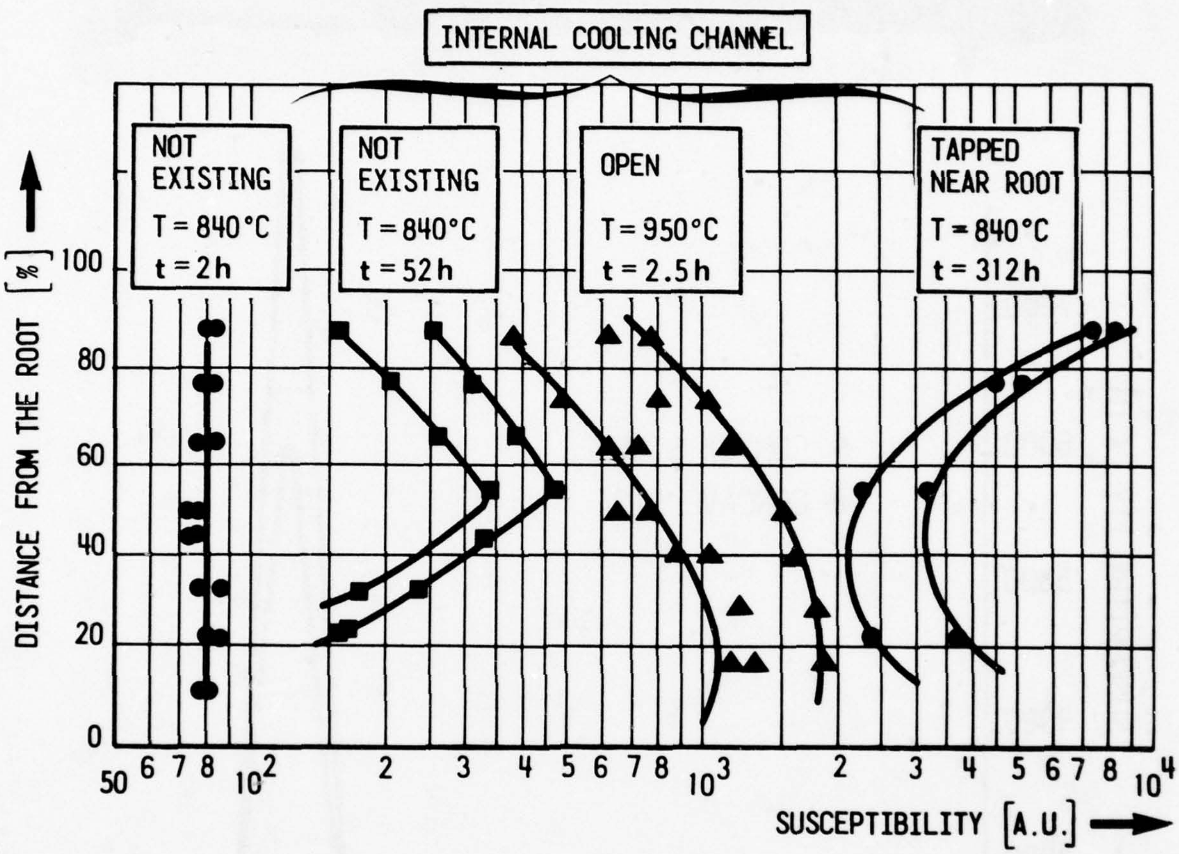

Fig.6 Typical cases of oxidation in the cooling channels of In-100 turbine blades

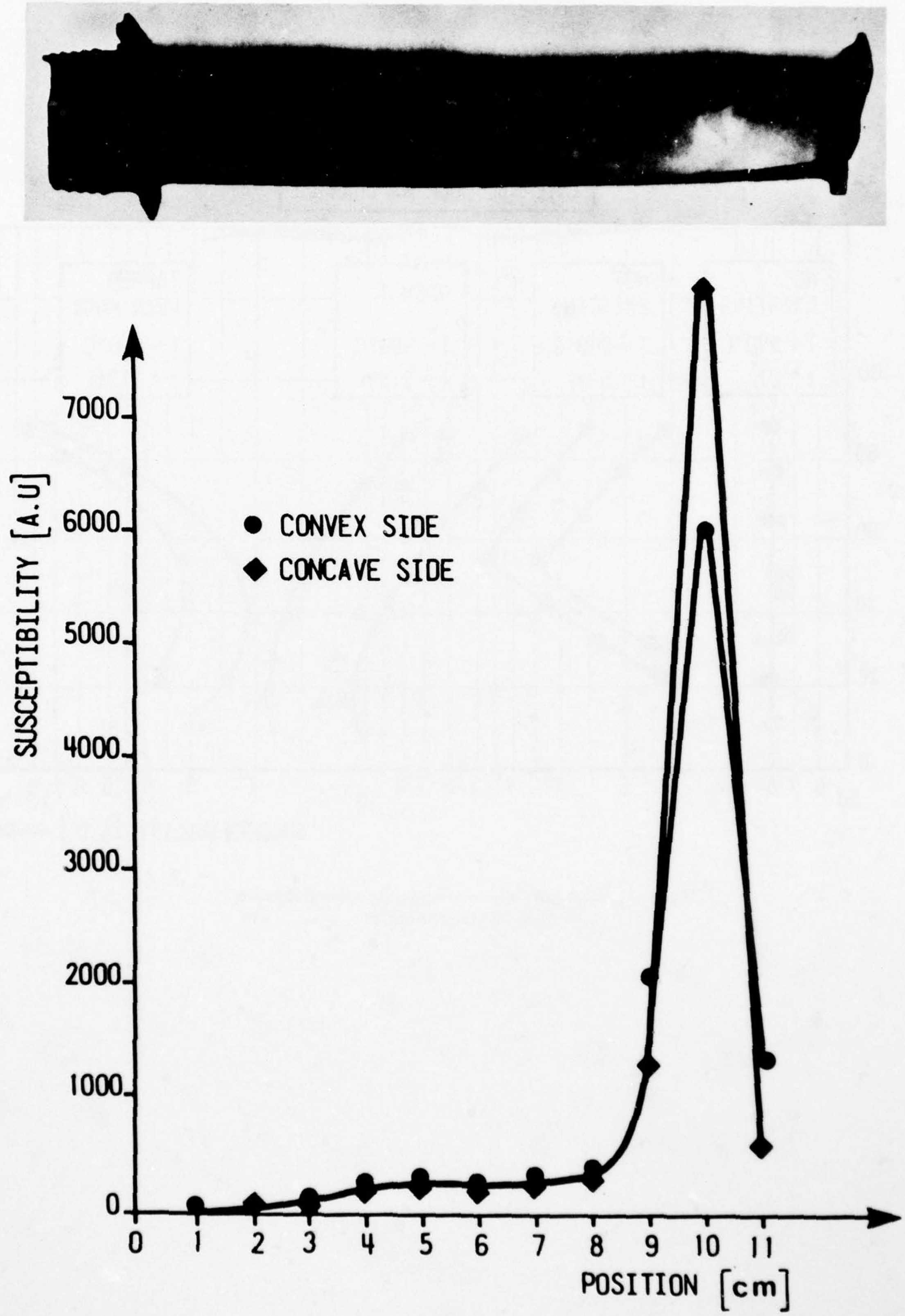

Fig.7 **A typical local oxidation at the convex side of the cooling channel, as shown by** *X-ray radiograph and evidenced by magnetic measurement*

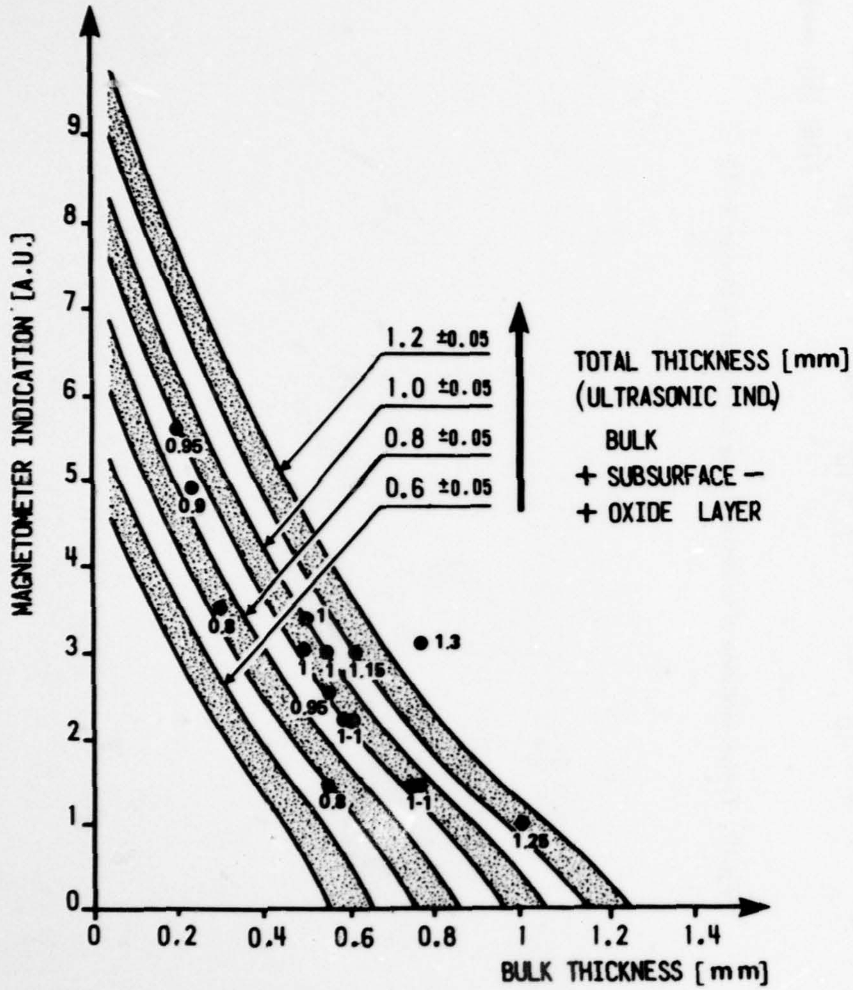

Fig.8 Correlation between bulk thickness remaining after corrosion, total thickness and magnetometer indication

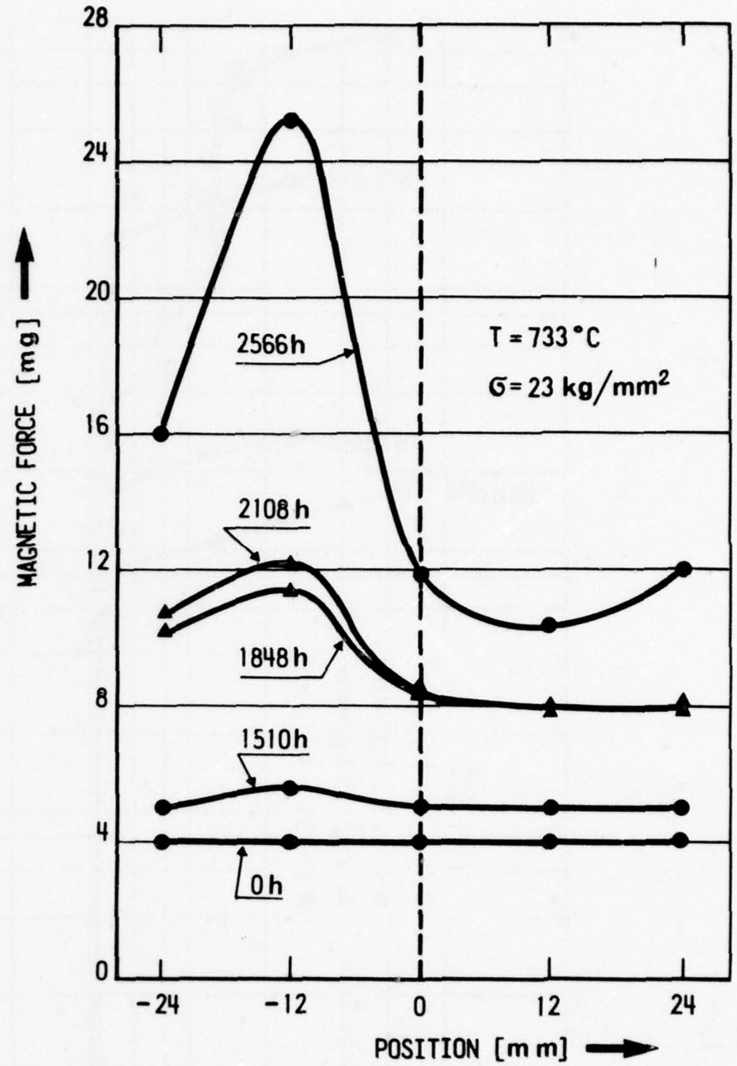

Fig.9 Oxidation during a creep corrosion experiment of Inconel X-750 samples

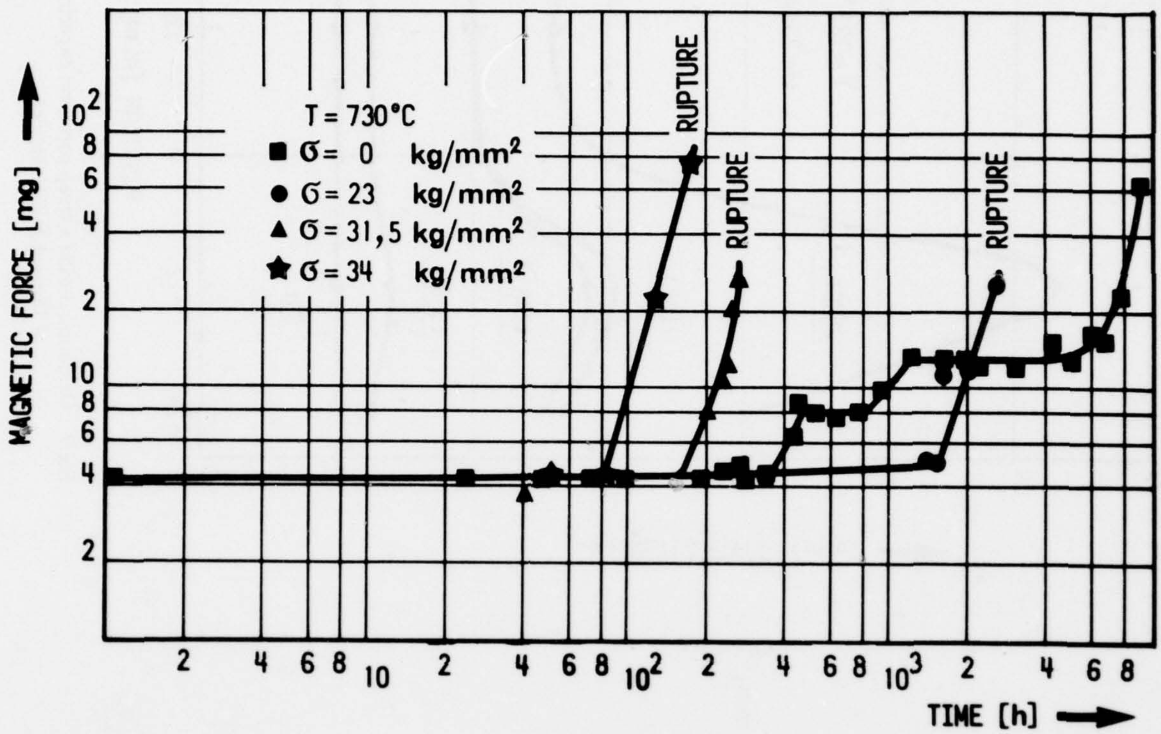

Fig.10 Typical evolution of oxidation during creep in air of Inconel X-750

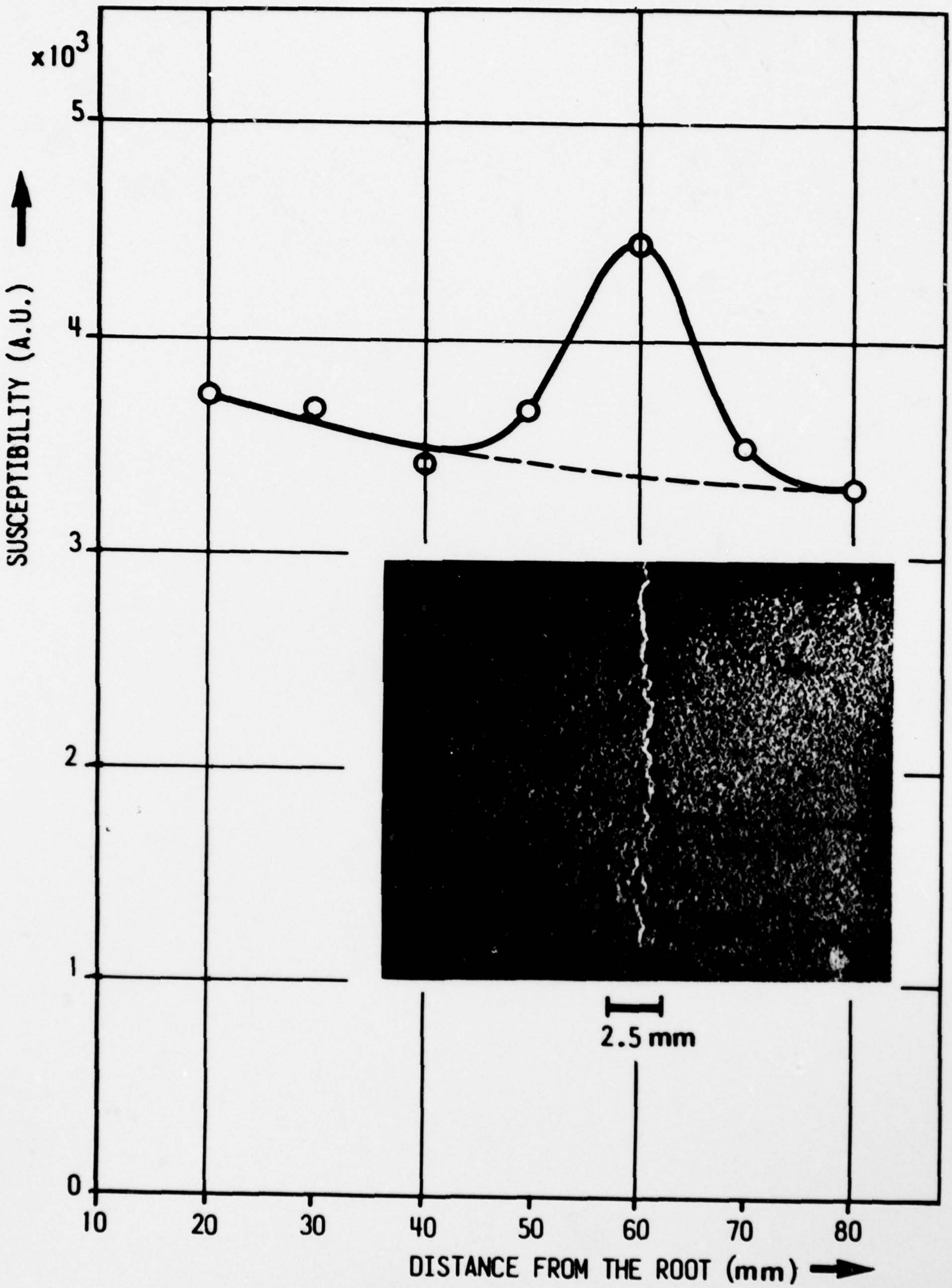

Fig.11 **Increase of apparent magnetic susceptibility near a crack in a power plant turbine blade of Inconel X-750 after 65000h service**

APPLICATION OF X-RAY DIFFRACTION STRESS MEASURING TECHNIQUES

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SUMMARY

X-ray diffraction stress measuring techniques can be applied to a wide variety of components. This paper describes several applications in detail in order to illustrate the advantages and limitations of the techniques. The variation of residual stress with position at the surface is illustrated for a machined aluminium alloy extrusion and for the region adjacent to a butt-welded steel plate. The variation of residual stress with position below the original surface is illustrated for shot-peened components and for a flow-formed maraging steel tube. The advantages of chemical polishing for layer removal are discussed. A knowledge of the residual stress distribution below a shot-peened surface can be used to determine the feasibility of peen-forming. The practical problems associated with unusual geometry and physical size of components are described.

INTRODUCTION

X-ray analysis is now a well-established method of determining the residual stresses present in engineering components. The principles of the technique have been widely publicised. An excellent manual is available[1] which gives extensive theoretical and practical details of the method. Recent developments in both techniques and applications were described at a recent conference[2]. Applications of the technique range from routine quality control procedures to detailed studies of the residual stress distribution within a given component.

Quality control procedures are based on rapid estimates of surface residual stress level and are necessarily non-destructive. High-speed measuring techniques have been developed using single-purpose diffractometers[3]. These procedures are useful for ensuring either that harmful levels of surface tensile stress are absent or that deliberately-introduced surface compressive stress levels are present. This type of application is in very limited use and will not be discussed further in this paper.

Detailed studies of residual stress distributions involve either measurements at different positions on the surface of a given component or measurements at different depths below the surface at one position on a component. This latter procedure, which is necessarily at least partially destructive, requires repeated removal of thin layers with stress measurement being made at the corresponding intervals below the original surface. The stress in the removed layers affects the subsequent measured values. Moore and Evans[4] developed equations which can be used to correct the measured values.

The most common limiting factor of the practical application of X-ray stress analysis is that of sample geometry. Stresses cannot be measured inside small tubes or at the bottom of narrow holes. Very large components require the use of either purpose-built portable diffractometers or X-ray stress cameras. Beryllium poses a special problem because of its very low absorption of X-radiation. This prevents the measurement of surface stresses in beryllium and most of its alloys.

X-ray stress analysis has the unique advantage that it can distinguish between the separate stresses in multi-phase materials. The most important commercial example is probably that of quenched steel which contains a proportion of retained austenite in a martensitic matrix. The amount of retain austenite is largely determined by the composition of the steel. In a given component the stress in the martensite phase may be compressive whereas the stress in the austenite phase may be tensile. It is therefore important to consider both stresses rather than try to predict an improvement in service performance simply on the basis of a compressively-stressed martensitic matrix.

The practical examples of stress analysis used in this paper illustrate the advantages of the technique, experimental problems and the metallurgical and fabrication variables which influence the distribution of residual stresses.

An essential limiting feature of the technique is the character of the area of the sample irradiated by the incident X-ray beam. This feature is discussed first to provide a basis for the discussion of the practical examples of stress analysis.

1 CHARACTER OF IRRADIATED AREA

The individual crystals in a polycrystalline material are made up of families of identical planes of atoms. Each family has a reasonably uniform interplanar spacing d_{hkl}. X-ray stress measurement depends upon the measurement of the lattice strain

normal to these planes, $\Delta d_{hkl}/d_{hkl}$. A beam of monochromatic X-rays irradiates an area of the component. At certain angles of incidence between the beam and the crystal planes, called Bragg angles θ, the X-rays are diffracted as if they were being reflected from the planes.

The geometry of diffraction for an X-ray diffractometer is shown in Fig.1. X-rays emitted from a line-shaped source S-S' are collimated to form a wedge-shaped divergent beam which irradiates a rectangular area of the flat sample surface ABCD. The angle of divergence, α, is readily controlled by means of divergence slits. The effective width, W, of the beam is normally the same as the fixed width of the line source. For most X-ray tubes this is between 10 and 20 mm. The length, L, of the irradiated rectangle depends upon α, θ and the distance, R, from the line source to the sample. Hence:

$$L = \alpha \ R \ \text{cosec}\theta \tag{1}$$

As a typical example if $\alpha = 2^{\circ}$, R = 170 mm and $\theta = 75^{\circ}$ then L = 6.1 mm

The first limiting condition is that the irradiated area ABCD must contain a fairly large number of crystals. This is because only a small fraction of the crystals within the irradiated area are favourably orientated with respect to the direction of the incident beam. These are the crystals which satisfy the Bragg condition for the particular planes hkl that:

$$n\lambda = 2 \ d_{hkl}\sin\theta \tag{2}$$

where n is an integer, λ is the wavelength of the monochromatic X-rays, d_{hkl} is the spacing of the 'reflecting' planes and θ is the Bragg angle for the planes hkl. The diffracted X-rays come to a focus at the receiving slit at C-C' and subsequently enter an intensity monitor.

It follows from Eq.(2) that a change Δd_{hkl} in the interplanar spacing d_{hkl}, induced either by applied or by residual stresses will cause a corresponding change $\Delta\theta$ in the Bragg angle θ. Hence:

$$\Delta\theta = \frac{-\Delta d_{hkl}.\tan\theta}{d_{hkl}} \tag{3}$$

Accurate measurements of the Bragg angle θ relative to that for material in the unstressed state will therefore give a measure of the strain perpendicular to the surface. Fig.2(a) shows that the small fraction of crystals which are favourably orientated act as a series of miniature strain gauges yielding a value of strain perpendicular to the surface, ε_z, where $\varepsilon_z = \Delta d_{hkl}/d_{hkl}$.

A second measure of strain, $\varepsilon_{\phi,\psi}$, is required in order to deduce the required strain, $\varepsilon_{\phi,\psi=90^{\circ}}$, parallel to the sample surface (see Fig.3). The second measure of strain is achieved by rotating the sample about the axis of the X-ray diffractometer (O-O' in Fig.1) by an angle ψ. After this rotation the length L of the irradiated rectangle changes slightly. Eq.(1) now takes the form:

$$L = \alpha \ R \ \text{cosec}(\theta + \psi) \tag{4}$$

A different fraction of the crystals in the irradiated area now satisfies the Bragg condition for diffraction. This is illustrated schematically in Fig.2(b) where these different crystals again act as miniature strain gauges but now give the strain, $\varepsilon_{\phi,\psi}$. It should be noted that the number of crystals in the irradiated area of a real sample and therefore the number in favourable orientations are much greater than those shown in Fig.2. When the sample is rotated about the diffractometer axis relative to the X-ray beam then the focussing geometry changes. This is illustrated in Fig.4. The intensity monitor should be moved to the new focussing position, F, for optimum intensity measurements.

A second limiting condition is that the intensity of the diffracted radiation is directly proportional to the size of the irradiated area. If this area is made very small then the intensity of the diffracted radiation becomes so low that accurate determination of the Bragg angle values is impossible. The effect of reducing the area can be offset to a limited extent by increasing the intensity of the incident radiation. Another alternative is to use film monitoring techniques but these are intrinsically less accurate than diffractometer methods. An irradiated area of 10 mm² is feasible which compares favourably with the size of strain gauges.

The theory of isotropic elasticity gives the following relationship between the measured elastic strain, $\varepsilon_{\phi,\psi}$, and the required surface stress, σ_ϕ :

$$\varepsilon_{\phi,\psi} = \frac{\nu + 1}{E} \sigma_\phi \sin^2\psi - \frac{\nu}{E}(\sigma_1+\sigma_2) \tag{5}$$

This is the equation which forms the basis of X-ray stress analysis. Eq.(5) can be utilised in a number of ways. The two most commonly used are the 'two-exposure' and the '$\sin^2\psi$' techniques. Details of these techniques are readily available[1,5]. The application of the theory of isotropic elasticity leads, however, to a third limiting condition for the application of the X-ray techniques. It is tacitly assumed that the measured lattice strains can be converted into residual stress values using bulk elastic property values. Closer inspection shows that there are two problems associated with this assumption. The first is that different specific crystal planes hkl have different reactions to applied stress. Hence we need to use experimentally-determined crystallographic elastic properties. The second problem is that of 'preferred orientation' in the polycrystalline sample.

It is well-known that the bulk elastic properties of materials can vary

substantially with preferred orientation direction. Heavily cold-rolled metals and hot-extruded Nimonic alloys are important examples of materials having substantial degrees of preferred orientation. The crystallographic elastic properties and the effect of preferred orientation can be determined using a calibration test piece of the type shown in Fig.5. The calibration test piece should be in the same metallurgical condition as that of the component requiring stress analysis. Strain gauges at S and S' measure the longitudinal and transverse strains respectively when known elastic loads are applied by a tensile test machine. This gives the bulk values of E and ν for the actual test sample material and hence allows for the presence of preferred orientation. The strain gauges have then been calibrated against known applied stresses. The calibration test piece is subsequently transferred to a four-point loading device mounted on the X-ray diffractometer. A series of elastic strains are then applied through the loading points at A. The values of ε_z and $\varepsilon_{\phi,\psi}$ are determined for each interval of elastic strain. These values are for a particular set of crystal planes hkl. Different values of ε_z and $\varepsilon_{\phi,\psi}$ are determined, if required, for other sets of crystal planes. The strains to be measured by the X-ray technique have then been calibrated by reference to the known stresses applied by the four-point loading device. It is, however, rarely convenient or necessary to go through the very time-consuming procedure of calibration. Published values for crystallographic elastic properties can be used. Bulk elastic properties of the material can also be used in the absence of substantial amounts of preferred orientation.

2 SURFACE RESIDUAL STRESS DISTRIBUTIONS

The residual stress at the surface of a component will normally vary with position on the surface. This variation may be small, as in the case of components shot-peened overall, or severe, as is observed with welded components. Machined components can show surprising variations which depend upon the type of machining operation and the amount of metal removed.

(a) Surface stress distribution for machined aluminium alloy extrusion.

Fig. 6 shows an aluminium alloy extrusion before and after machining off of the flanges. Residual stress measurements were required at different positions on the surface of both test pieces. The particular point of interest in this example is the surface residual stress distribution around the circumference of the machined extrusion. Fig.7 shows how the residual stress varies in the region of a single machined flange. The stress level varies from severe tensile to severe compressive over a few millimetres of an apparently uniform surface. Variations in the amount of plastic deformation associated with the machining operation gave rise to the observed residual stress distribution. The variation in intensity of the diffraction peak (see Fig.7) which accompanies the variation in residual stress is due to the preferred orientation induced by the machining operation.

The curved nature of the sample surface adds a fourth limiting condition to the application of the X-ray technique. Focussing of the diffracted beam becomes increasingly difficult as the radius of the curved surface decreases. When stress measurements tangential to the axis of the sample are required, as in this example, the divergence of the incident X-ray beam must be restricted. Stresses parallel to the axis require that the width, W, of the divergent beam must be restricted. Restriction can be effected either by using appropriate collimating slits at 90° to the divergence slits or by masking the sample surface.

(b) Surface stress distribution adjacent to butt-welded steel plates

Fig. 8 shows a test piece made by double-vee butt welding of steel plates. Residual stresses were measured at the surface of the parent plate for a series of positions on a line perpendicular to the weld, M-M'. The irradiated area for each measurement was 12 mm x 1 mm with the 12 mm being parallel to the weld. This size of test piece was convenient for the X-ray diffractometer being used although much larger samples could be examined. The size of the irradiated area was determined directly by the restricted divergence of the X-ray beam. For more complex welded (and other) components an alternative would have been to restrict the irradiated area by masking. Masking for steel components is readily effected by using lead-backed adhesive tape. An appropriate area is cut from the centre of a piece of tape. Irradiation of the lead mask does contribute to the background radiation received by the monitor but not to the diffraction peak (hkl=211) itself. A more acceptable masking material is one having a similar scattering power for X-rays to that of the sample. Austenitic steel foil can be used for ferritic samples but being less flexible it is less convenient than lead foil. Masks should only be used to precisely define the irradiated area. Restriction of the incident X-ray beam should be carried out as far as possible.

Fig. 9 shows the measured residual stress distributions for test pieces welded from cold-rolled plate and from annealed plate. There is a very significant difference between the two stress distributions. The region immediately adjacent to the welded cold-rolled plate has a surface tensile residual stress. Further away from the weld the surface stress becomes compressive and finally tensile again. The welded annealed plate, on the other hand, has a surface compressive stress for the whole of the corresponding region.

It is well-known that the actual weld metal normally contains high tensile residual stresses. The surface stresses in the weld itself can be relieved either thermally or mechanically. Alloying can also be used to increase the basic strength of the weld metal relative to the parent metal. This can then compensate for any deficiencies in

terms of the cast structure and the tensile residual stress. The parent metal adjacent to the weld, corresponding to the heat-affected zone, then becomes the weakest region. A surface tensile residual stress here, together with the weakening due to the thermal cycle, will then be a potential source of failure. Shot-peening is often used to produce a protective skin of compressively-stressed material in the weld and heat-affected zones.

3 SUB-SURFACE RESIDUAL STRESS DISTRIBUTIONS

Measurements of residual stress below the original surface of a component are necessarily destructive. These measurements are, however, often necessary because surface measurements alone would give a misleading impression of the significance of the residual stresses present in a component. Most applications are concerned with a thin surface layer of material which has either been deliberately hardened, for example by carburising, or has had stresses induced accidentally, as in the case of surface grinding or machining. Complete stress distributions are necessary to predict distortion whereas the stress distribution in a thin surface layer generally controls fatigue performance.

(a) Sub-surface stress distribution in a flow-formed maraging steel tube.

Fig.10 shows a portion of a thin-walled steel tube, flow-formed from a maraging steel, before and after slitting parallel to the axis of the tube. The expansion of the tube after slitting would indicate the presence of tensile residual stresses at the outer surface tangential to the tube axis. Surface stress measurements at several positions on the outer surface revealed, however, that the stress was compressive. Faced with this anomaly a survey of the residual stress distribution throughout the section was necessary. This investigation posed experimental problems because the tube wall thickness was only 400 μm. Very thin layers of material had to be uniformly removed from the outside of the sample and the relatively flimsy sample had to be held securely in an X-ray diffractometer. Layer removal was effected by taking a 25 mm wide band from the tube, protecting the inner surface with lead-backed masking tape and immersing the band in a chemical polishing solution.

Chemical polishing is particularly useful for stress analysis work because uniform layer removal over large areas of sample can easily be obtained. The evolution of gas at the sample surface also prevents the surface from reaching a temperature at which stress relief occurs. In this particular example a mixture of 20% nitric, 5% sulphuric and 5% phosphoric acid in water was used. Subsequent experience has shown that even better results can be obtained with steels using a mixture of 90% 100 volume hydrogen peroxide, 5% hydrofluoric acid and 10% water. The extent of layer removal was determined by weighing the band after each chemical polish. Residual stress measurements at a series of depths below the original surface gave the results shown in Fig.11. These results have been corrected for the effects of stress in the removed layers[4]. Mounting of the band was done using double-sided adhesive tape and a circular former attached to the X-ray diffractometer. The results show how the compressive stress on the outer surface rapidly gives way to a sub-surface tensile stress. This tensile stress subsequently reverts to compressive stress before finally becoming tensile towards the inner surface of the tube. The bending moments associated with the stress distribution are now consistent with the observed behaviour on slitting the tube.

(b) Sub-surface stress distributions in carburised steel components.

Figs.12 and 13 show the results of residual stress measurements made at different levels below the surface of gas-carburised EN353 steel components. Two different carbon levels and depths of case had been produced. The object of this investigation was to determine the effects of carbon content, case depth and subsequent shot-peening on the residual stress distribution. The component carburised to a 0.74% maximum carbon level and to a depth of 1.8 mm has an unsatisfactory residual stress distribution. A substantial level of tensile stress exists at the surface which would promote fatigue crack nucleation. Shot-peening of this sample has, however, substituted a beneficial compressive stress at and just below the surface.

The sample carburised to a 0.48% maximum carbon level with a case depth of 1.0 mm has a satisfactory residual stress distribution. The surface stress is compressive and shot-peening only serves to increase the level of compressive stress. Shot-peening has affected a deeper surface layer for the 0.48% maximum carbon sample than for the 0.74% maximum carbon sample. This is because the case is correspondingly softer. The development of compressive stresses by shot-peening is largely due to the transformation of retained austenite to martensite.

(c) Sub-surface stresses and peen-forming.

A knowledge of the residual stress distribution induced by shot-peening is useful in determining the feasibility of peen-forming. This process has a variety of applications which includes the shaping of wing panels. The major principle involved in peen-forming is that a surface force is generated from the compressive stresses introduced into one surface by shot-peening. This force then depends upon the generation of a sufficiently high level of stress at a sufficient depth so that the resulting force will have the required bending moment.

Fig.14 shows an idealised form of the residual stress distribution that is induced by the shot-peening of an initially stress-free strip. The level of the compressive stress near to the peened surface is largely determined for real materials by the yield strength. The depth of the compressively-stressed skin is largely determined by the size of shot used. An approximate value for the bending moment, M, can be estimated and substituted into the basic equation:

$$M = E.I/R \qquad (6)$$

where I is the second moment of area and R is the radius of curvature. This then gives an approximate value for the degree of bending that can be achieved. In the example shown of a rectangular section steel strip then the corresponding radius would be 700 mm. In an actual peen-formed component the bending involved would have reduced the level of compressive stress in the peened surface and would have induced a compressive stress in the opposite surface.

The approach outlined above is, of course, simplified relative to real situations. In practice, curvature about two axes would result from the shot-peening of an unrestrained sheet. This double curvature is a feature of the Almen gauges used as a control for shot-peening operations. Curvature about one axis is restricted in peen-forming operations in order to produce the required shape.

4 SINGLE STRESS MEASUREMENTS

Single stress measurements are used mainly either as a quality control check or as part of an investigation involving a series of samples. Fig.15 shows an example of quality control checking. The component shown is an intermediate compressor bearing from an RB211 engine. Precision grinding of the bearing surface is carried out not only to ensure dimensional accuracy and surface quality but also to produce a compressive stress. Grinding can produce a wide range of effects from tensile stresses high enough to produce cracking down to compressive stresses which are a substantial fraction of the yield strength. In a highly-stressed component it is therefore important to ensure that the grinding regime introduces beneficial compressive stresses. Values in the region of -300 MN/m^2 for the tangential residual stress are commonly reached with this particular component. Single measurements on a selection of components can then be used either for quality control purposes or for investigating proposed variations to the grinding procedure.

The experimental problems associated with the component shown in Fig.15 centred on the double curvature of the bearing surface and the weight of the component. The double curvature problem was reduced by using masking to restrict the size of the irradiated area as far as possible. A stress-free standard of the same geometry as that of the bearing surface was used to reduce measurement errors. The magnitude of the weight problem depends upon the type of diffractometer used. In the case of a horizontal-axis diffractometer of the type used here the problem is greater than for a vertical-axis diffractometer. With this diffractometer counterbalancing of the component was used to ensure that the irradiated surface stayed on the diffractometer axis during rotation.

5 CONCLUSIONS

The examples of residual stress analysis given in this paper were chosen to illustrate the wide range of useful applications that are possible for the X-ray stress measuring techniques. Restrictions on the application of the techniques mainly depend upon the following:

(i) The irradiated area must contain a fairly large number of crystals.

(ii) The size of the irradiated area must be large enough to give a reasonable intensity of diffracted radiation.

(iii) Experimentally-determined values of crystallographic elastic properties are required together with a knowledge of the extent and effect of preferred orientation.

(iv) Curvature of a component surface leads to focussing problems. The greater the degree of curvature the more the size of the irradiated area must be restricted. X-ray stress camera techniques may then be preferred to diffractometer techniques.

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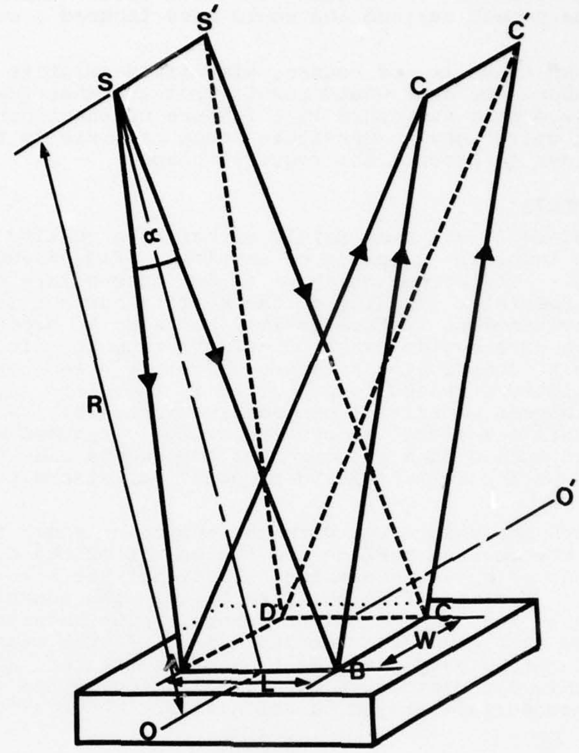

Fig.1 Schematic representation of diffraction from a flat sample

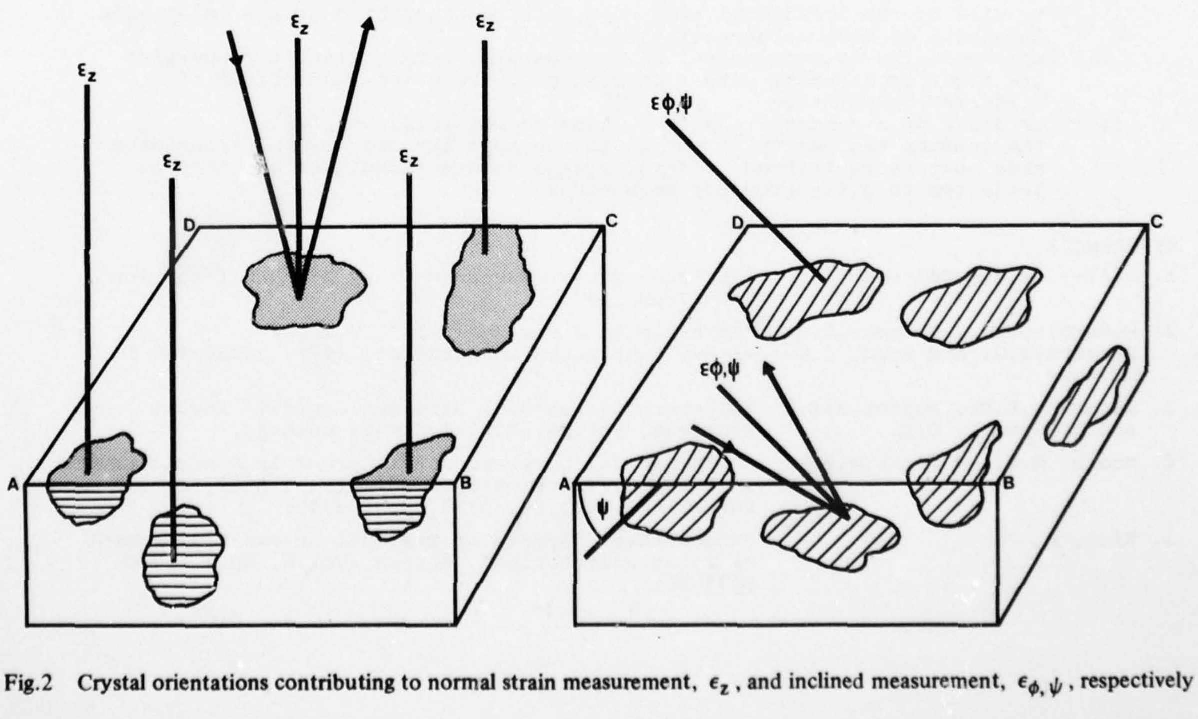

Fig.2 Crystal orientations contributing to normal strain measurement, ϵ_z, and inclined measurement, $\epsilon_{\phi,\psi}$, respectively

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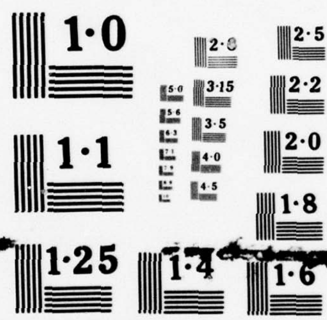

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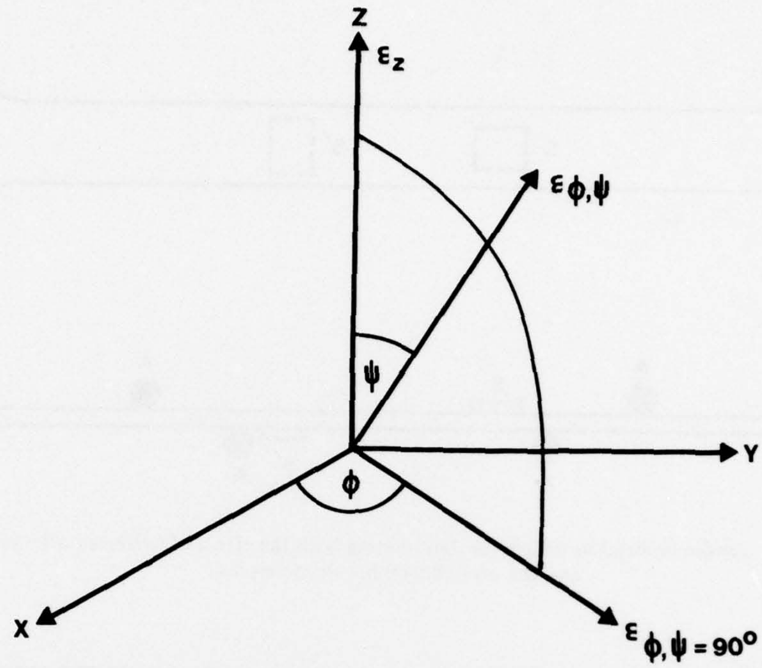


Fig.3 Components of stress and strain used in X-ray stress analysis

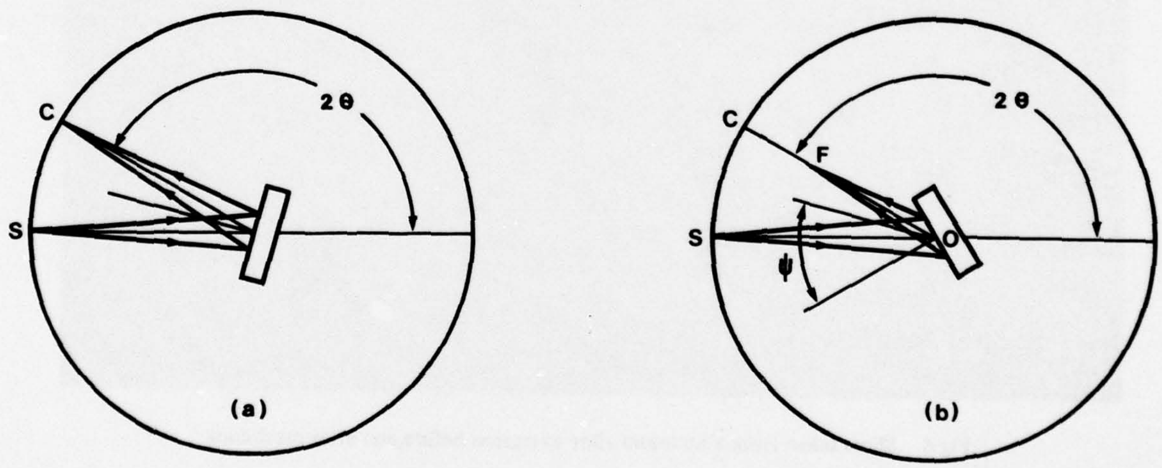


Fig.4 Focussing geometry for flat samples (a) when $\psi = 0°$ and (b) when $\psi = 45°$

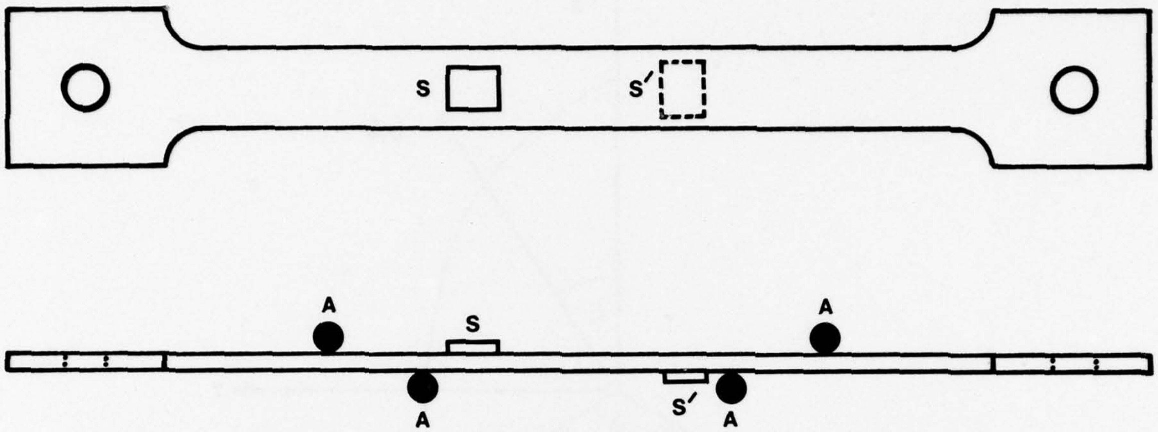


Fig.5 Tensile calibration sample for determining both the effect of preferred orientation and the crystallographic elastic moduli

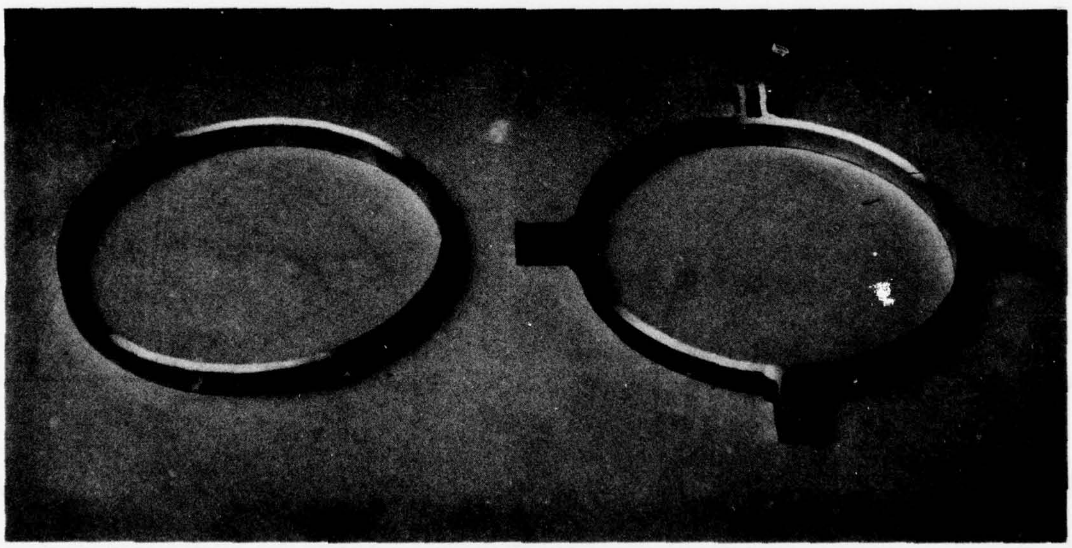
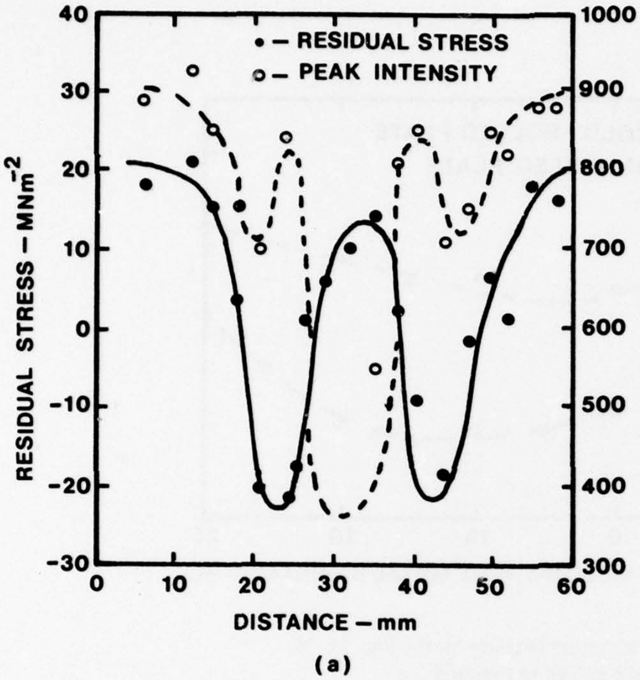


Fig.6 Slices taken from aluminium alloy extrusion before and after machining



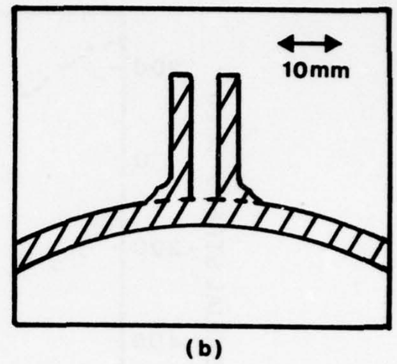


Fig.7 (a) Residual stress and intensity distributions for the outer surface of the machined extrusion. The corresponding region before machining is shown in (b)

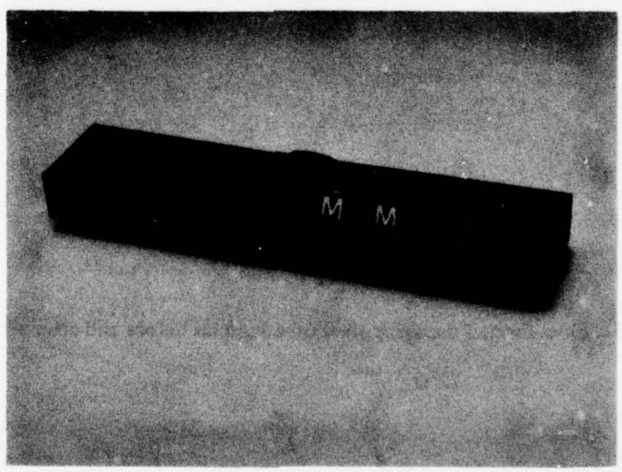


Fig.8 Double-vee butt welded test block: showing the line of stress measurement M–M′

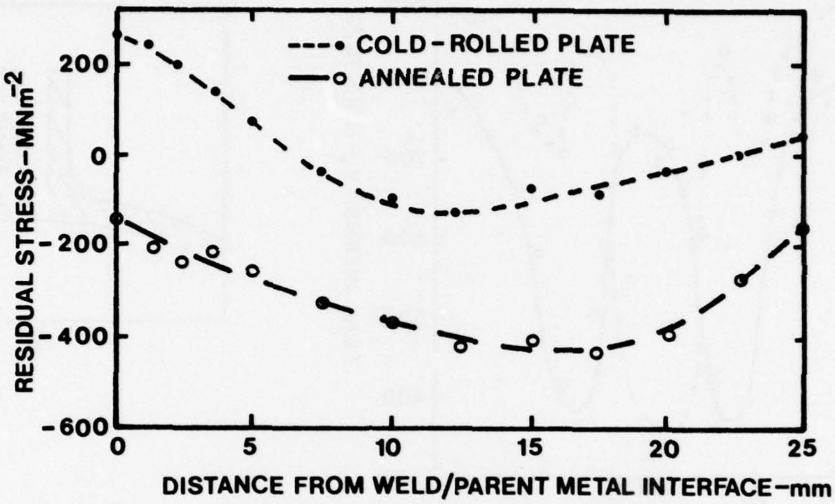


Fig.9 Residual stress measurements taken on the line M–M′ of the sample shown in Figure 8

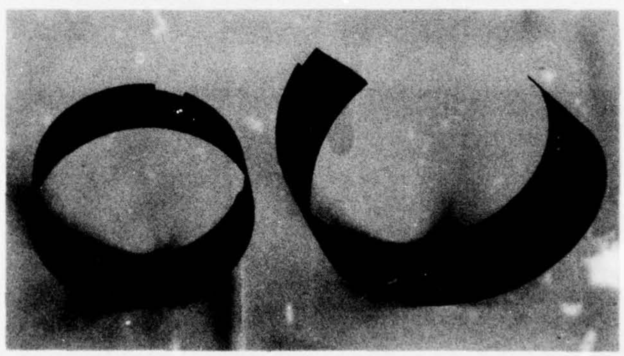


Fig.10 Flow-formed maraging steel tube samples before and after slitting

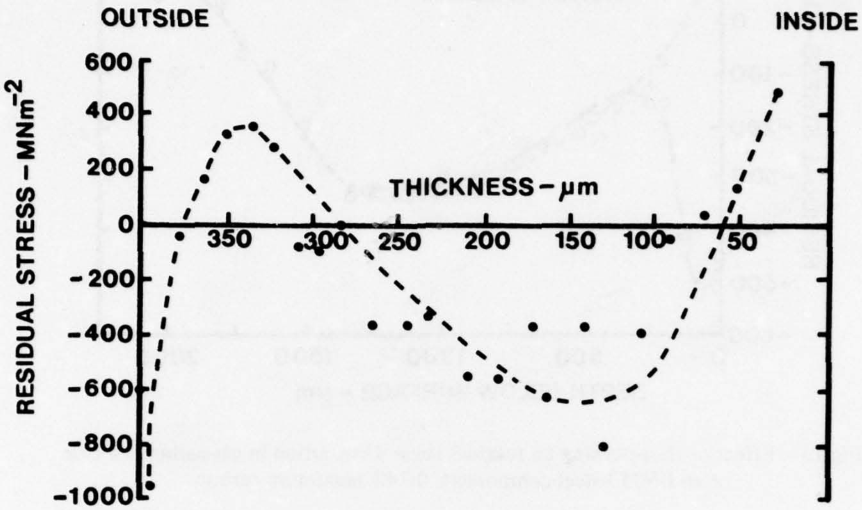


Fig.11 Residual stress distribution at and below the surface of a test specimen of flow-formed maraging steel tube

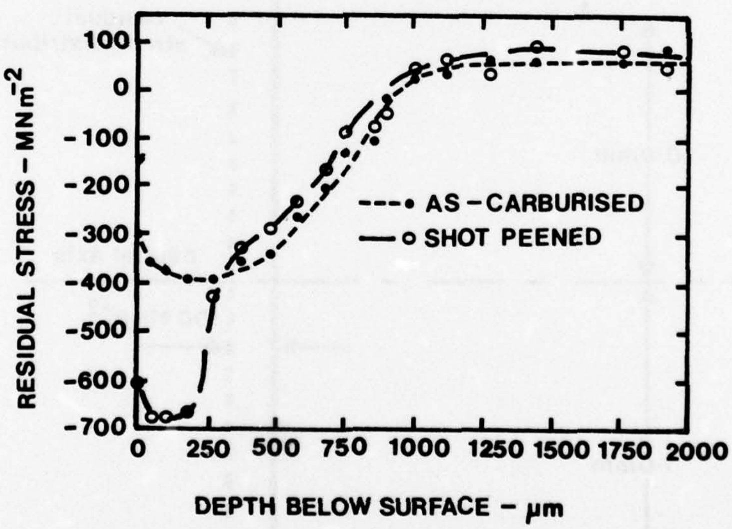


Fig.12 Effect of shot-peening on residual stress distribution in gas-carburised case of an EN353 steel component, 0.48% maximum carbon

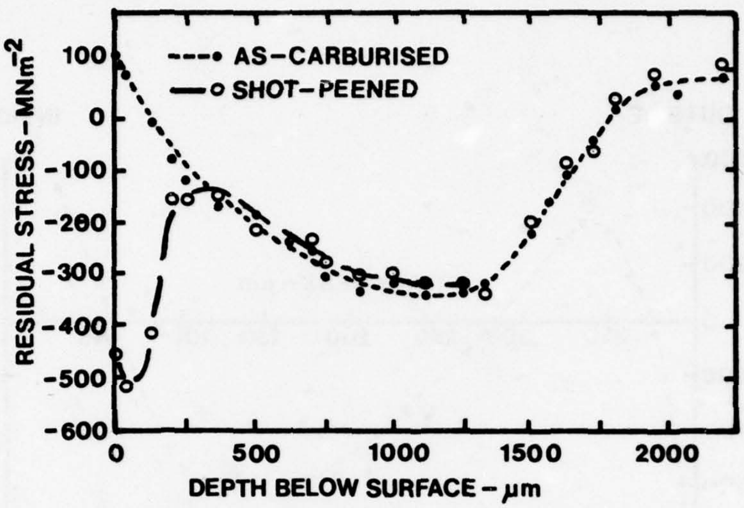


Fig.13 Effect of shot-peening on residual stress distribution in gas-carburised case of an EN353 steel component, 0.74% maximum carbon

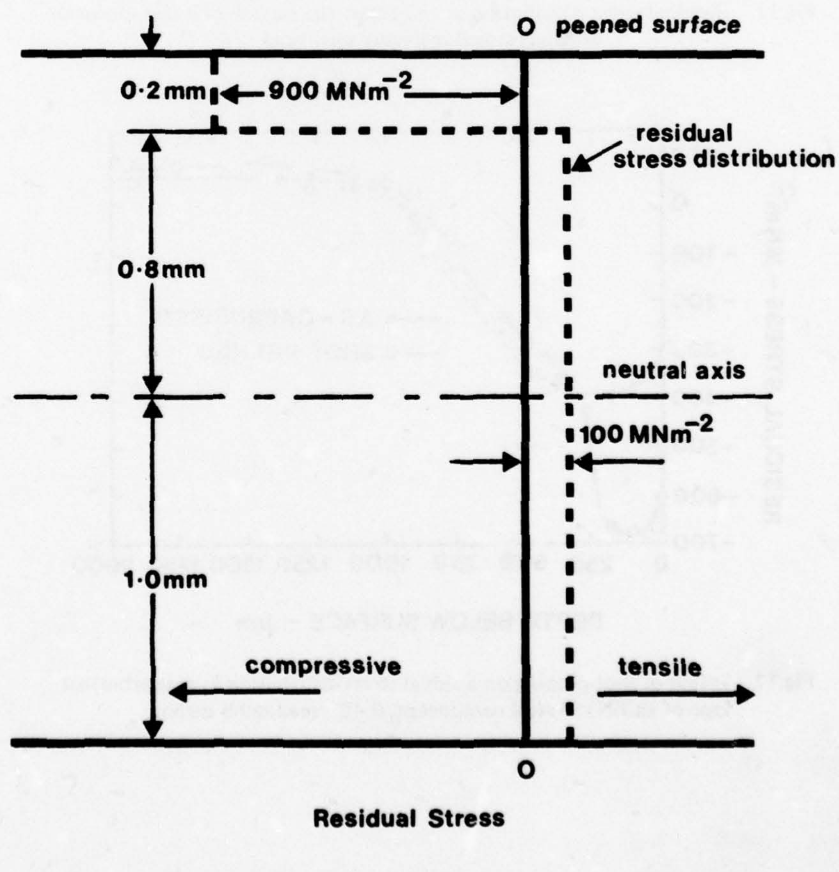


Fig.14 Idealised stress distribution in a clamped strip

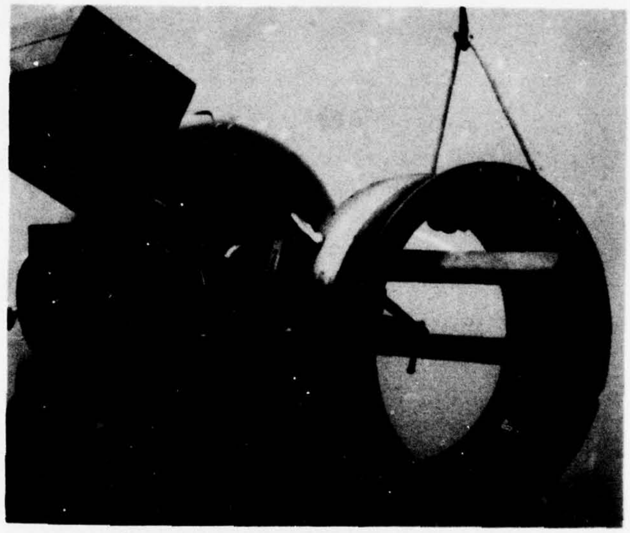


Fig.15 General view of diffractometer being used to measure residual stress in RB211 bearing

X-RAY DIFFRACTION: FROM STRUCTURAL X-RAY DIFFRACTOGRAPHY TO X-RAY OSCILLOGRAPHIC DIFFRACTOSCOPY

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This paper deals with the development of a method of fast inspection of jet engine compressor blades and is divided into three Parts:

– the first one shows the results obtained by classical X-ray diffractography, which utilizes filtered radiation and plane X-ray films;

– the second one illustrates the oscillographic fast inspection, with fixed sample and rotating counter-carrying arm; the results obtained by this method are correlated with those obtained by the previous one;

– the third one reports the oscillographic observations on rotating compressor steel blades. The results are compared with those obtained by eddy currents.

PART 1

This Part concerns the results of a diffractographic test performed on compressor blades taken from a turbojet in service. The purpose was to assess the practical possibility of utilizing a blade, as a function of the structure of the material, after a preset number of working hours. The usefulness of this test is well known:

– to detect an early decay of the material in order to prevent failures;

– to delay the end in service of the pieces.

The consequences, both operational and economic, are readily understandable.

The diffractographic method with X-ray plane film has been adopted (see Figure 1). The radiation was the Fe K-alpha, filtered through a Mn filter, radiation got from a tube (X-ray source) fed by 50 kV and 8 mA.

Blades were of A1-alloy; the experimental procedure was suitable to take diffraction rings corresponding to the matrix structure – lattice planes ((100)) – and to two phases dispersed in the matrix. The Figures 2, 3, 5, 6, 7 and 8 exemplify the critical stage of the structural evolution of the material, established in 108 examined samples, pertaining to three stages of the jet engine compressor in study.

Figures 2 and 3 concern blades of the second and the third stage, Figures 5, 6, and 7, as well as 8, blades of the 4th stage of the compressor. The operating hours were 2371, 2506, 2618 and 3160. The linear mark visible on each diffraction pattern corresponds to a direction, normal to the longitudinal axis of the blade, oriented towards the part of greater thickness of it. All the patterns were taken in strictly constant geometric conditions. The incident beam irradiated a circular surface, having a diameter of 2 mm, located on the back of blades and at 1/3 of tr[illegible]itudinal development.

The phenomena shown by the patterns indicate the existence of a critical stage of decay (about 2500 hours), starting from which the operational oldness of the material begins. Since then, in normal operating conditions, the extension of life of a component is to be considered limited and nearly constant. Figure 9(b) shows, for comparison, the diffraction pattern of a blade, taken by a conical diffractograph (1). The diffraction arcs of the figure correspond in the following way:

– the three innermost ones, to the diffraction rings visible in the previously-cited figures;

– the two outermost ones, to diffraction maxima produced by the lattice planes ((111)) and ((311)) of the matrix, these maxima, given by beams back-diffracted almost orthogonally to the incident beam, are not observed in the plane film method.

PART 2

Using X-ray diffraction in the practice of NDT has been, till now, strongly hindered because the techniques connected with it are considered of not immediate application by mean-level technical personnel and, besides, not suitable to give evident and meaningful instrumental responses in a short time interval (order of minutes).

This part illustrates a device, based on the principles of the conical diffractograph and diffractometer (1) (2) and of the oscillographic diffractometer (3), suitable to enable fast evidencing of changes in material structures.

Figure 9(a) shows the device. The photograph displays a diaphragm-collimator system (A), from which X-rays emerge, produced by a source B (tube), almost orthogonal to the plane of the figure and the head of which is covered by the electrical motor C, which has the function of driving the diffractometer. The irradiated sample is D. The figure shows the detector E (in this case, proportional with filling of Xe), with the lead which connects it to its pre-amplifier F and, from this one, to high voltage generator and to counting device (G). The exit diaphragm H is also visible; it is equippable with a momochromator (proportional counters are besides, as well known, discriminable). The detector E is mounted on a slide (I), running on an arm (K), the radius of curvature of which has centred in the geometric centre L of the small portion (order of cm^2) of the surface, on which X-rays impinge.

The experimental procedure is as follows:

After feeding the X-ray source and beginning the sample irradiation, the slide (I) is dispaced along the arm (K), until the geometry of the system corresponds to the counting, by the detector, of a maximum of diffracted intensity. Then, the detector-carrying arm is automatically rotated, by the electrical motor C. This arm rotates around the axis passing through A (centre of diaphragm-collimator) and L (centre of the irradiated surface). The diffractometer describes an almost complete turn in 1 or 2 minutes, or less. It rotates around the primary beam. The displacement of the slide along the arm K, in order to get information on the stresses in the sample, connected with changes of the angle 2θ ($180° - A\hat{L}H$), can be achieved by another electrical motor, not displayed in the figure. Instead of a curved counter-carrying arm, a linear arm could be adopted (see also Figure 12). This geometry, closer to the concept of conical diffractograph, exhibits some peculiar advantages. The aperture of the cone, described by the arm during its motion, can be varied and the system can be adapted to the particular geometries of the components under test (for instance, the distance source-sample can be modified, the geometric hindrance of the arm can be avoided, etc.). The results, gotten by the device shown in Figure 9(a) are displayed in the Figures 5, 6, 7 and 8. They show diffraction patterns got by sending the voltage output, coming out from the ratemeter of the counting device, to an oscillograph, so that the Y (vertical) axis corresponds to the intensity of the diffracted radiation and the X (horizontal) axis – axis of times – to a quantity proportional to the angle described, by the counter-carrying arm, during the revolution around the axis AL. The triggering of the track in X-axis is synchronized with the beginning of the motion of the arm. For the operational parameters see Table 1.

Figure 4 shows a pattern taken with the arm stopped. Therefore, intensity fluctuations are due only to the stochastic nature of X-rays emission. So, it is our "zero" for evaluating the next patterns. Each of the Figures 5 – 8 displays a plane film X-ray diffraction pattern together with an oscillographic pattern, taken from those pertaining to the blades of the same stage and number of operating hours. The complete series of patterns is available c/o the author. Figure 5 pattern shows a distribution of intensity along a diffraction ring 311 (2371 operating hours). There is evidently a continuous distribution, with not well evidenced minima and maxima. This, in turn, is evidence of a structure consisting of crystallites whose linear dimensions, orthogonally to ((311)) planes, are of the order of magnitude less than that of the irradiated surface. For these crystallites, besides, there is not a preferred orientation. Figures 6 and 7 display, on the contrary, well evidenced discontinuities in patterns, with marked maxima; this is evidence of the presence of just few crystallites whose sections, orthogonally to the incident beam, are comparable with the irradiated surface (operating hours 2506 and 2618). The feature of the patterns is also typical of a strong directionality in the orientation of the crystallites in a polycrystalline sample. The next pattern (Figure 8, working hours 3160) evidences a partial recovery of the initial structure.

There is coincidence of information got by X-ray classical diffractography and by oscillographic diffractography; the latter is however much faster than the former (1 minute against 6 hours). The validity of the method goes far beyond the example reported here: wing attachments, fuselages, engine and airframe components could be inspected, in several instances without disassembling.

PART 3

X-ray oscillographic diffractography and eddy currents testing have been applied in parallel to steel blades taken, after different operating hours, from the same compressor as the light alloy blades. The operating hours pertaining to the blades object of this work are the same as those of the Al-alloy blades previously treated. Figure 10 displays oscillographic diffraction patterns taken according to the conditions illustrated in Table 2, which also includes the parameters concerning eddy currents tests.

Figure 11 is, as usual, the "zero" of the oscillographic diffraction patterns, as it has been taken in the same conditions of the ones of Figure 10, but without rotating the blade. On each of the patterns, the area A, corresponding to each cycle, has been measured by a planimeter having a prevision of $0.1\ cm^2$.

For evaluating the results got by eddy currents, the differences ΔV_{max} between the values of maximum voltages taken from the ends of the metric coil, with and without blade, has been determined by an oscillograph, whereas the differences between the corresponding RMS values were measured by a digital voltmeter. These values are indicated by ΔV_{eff} (differences between RMS values). The ratios $A/\Delta V_{max}$ and $A/\Delta V_{eff}$ are listed in Table 3. They do not need any explication. The total diffracted intensity is proportional to the voltage changes measured in eddy current testing system. Figure 12 shows the diffractometric device: A is the steel blade which rotates around a horizontal axis (period 1 – 2 s). S is the source of X-rays (tube), B the diaphragm-collimator system, D the detector, whose output feeds the Y-input of the oscillograph.

CONCLUSIONS

Oscillographic X-ray diffraction methods of testing (X-ray oscillographic diffractoscopy) have proved to be of general validity for fast NDT of materials. They do retain the meaning and the richness of information obtainable by classical X-ray diffraction methods, but are much faster in performance and simpler to interpret.

TABLE 1

Source of X rays (tube)	
– Target	Cr
– Voltage (kV)	20
– Current (mA)	6
Detector	
– Kind	Proportional, filled with Xe
– Voltage (V)	1900
– Output voltage pulses gain	1000
Discrimination	
– Base (V)	8
– Channel (V)	5
Analytical radiation	Cr K-Alpha
– Wavelength (Å)	2.291
Diaphragms	
– Inlet (circular)	ϕ 5 mm
– Exit (linear)	1 x 12mm
Filter	V
Diffracting lattice planes	311
– Interplanar spacing (Å)	1.221
– Bragg angle	69°45′ θ
Distance between sample and focal spot (source)	25 mm
Incident beam aperture	4°12′
Oscillographic device	
– Horizontal sensitivity	5 s/cm
– Vertical sensitivity	1 V/cm
– Grating dimensions	6 x 10 cm

TABLE 2

Source of X rays (tube)	
– Target	Fe
– Voltage (kV)	40
– Current (mA)	12
Detector	
– Kind	Proportional, filled with Xe
– Voltage (V)	2000
– Output voltage pulses gain	1250
Discrimination	
– Base (V)	20
– Channel (V)	30
Analytical radiation	Fe K-Alpha
– Wavelength (Å)	1.937
Diaphragms	
– Inlet (linear)	2 x 12 mm
– Exit (linear)	1 x 12 mm
Filter	Hn
Diffracting lattice planes	110 alpha-phase
– Interplanar spacing (Å)	2.027
– Bragg angle	$28°36'\ \theta$
Incident beam aperture	2°
Distance between sample and focal spot (source)	17 cm
Oscillographic device	
– Horizontal sensitivity	0,5 s/cm
– Vertical sensitivity	1 V/cm
– Grating dimensions	6 x 10 cm
Eddy currents analyzer	
– Frequency	15 kHz
– Turns/cm	100
– Dimensions of turns	35 x 10 (in mm)
– Voltage across the coil (empty)	30 Veff
– Waveform	sinusoidal

TABLE 3

Blade nr.	Ratio $A/\Delta V_{max}$ (cm^2/V)	Ratio $A/\Delta V_{eff}$ (cm^2/V)
1	15	19
2	15	18
3	14	17
4	15	19
5	15	18
6	14	18
7	16	19
8	15	19
9	16	19
10	14	18

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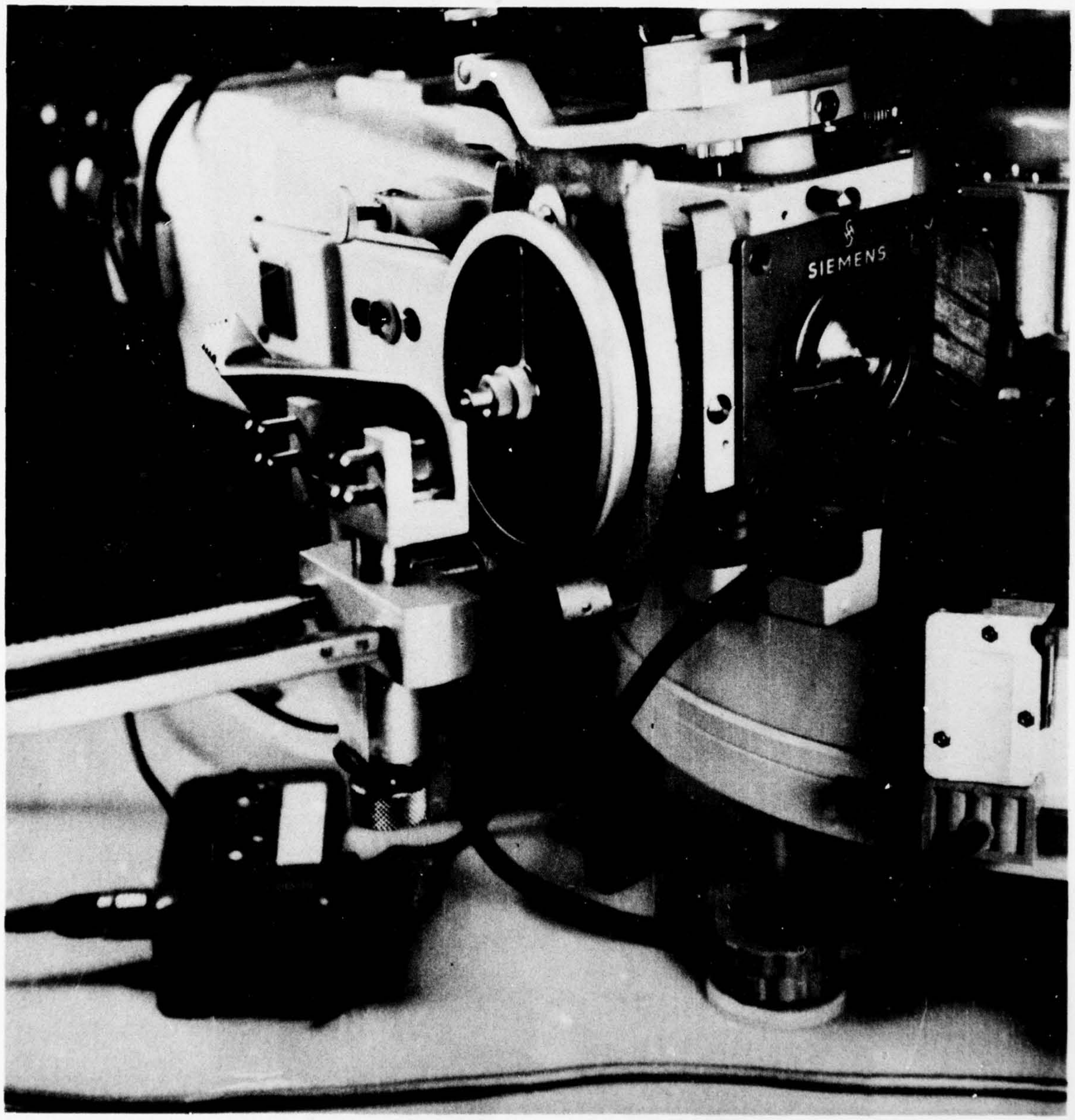


Figure 1

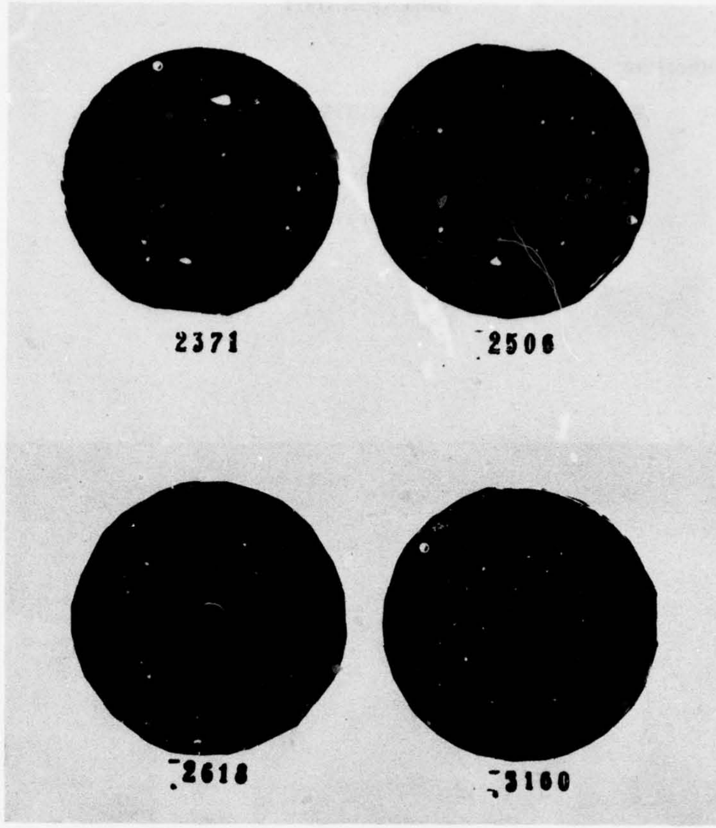


Figure 2

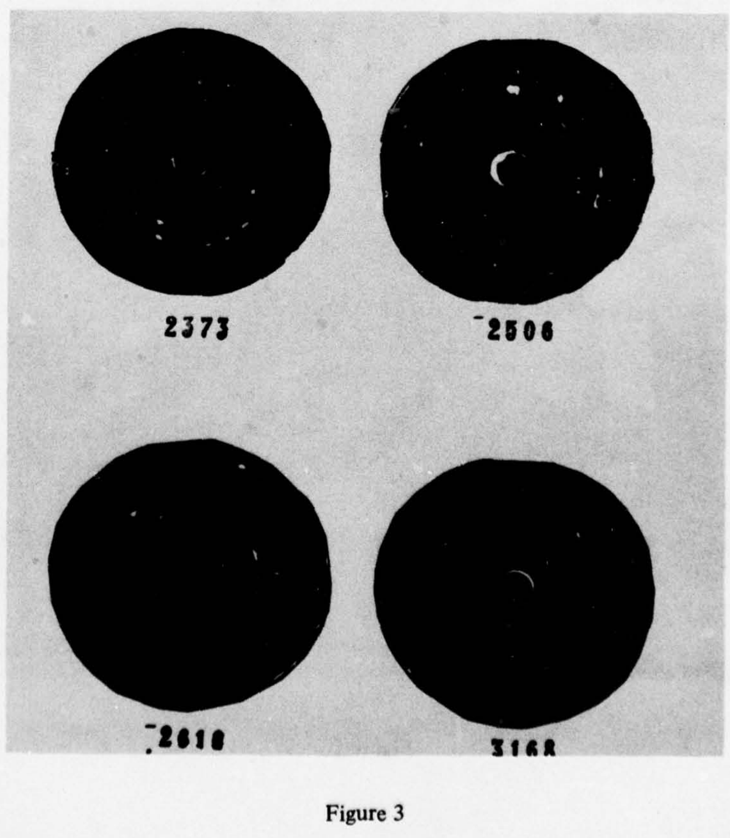


Figure 3

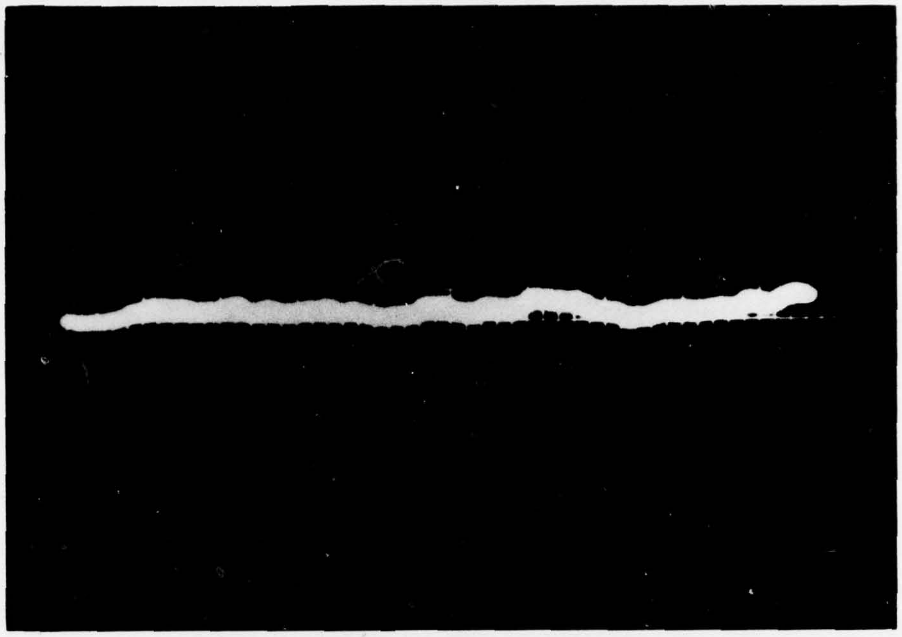


Figure 4

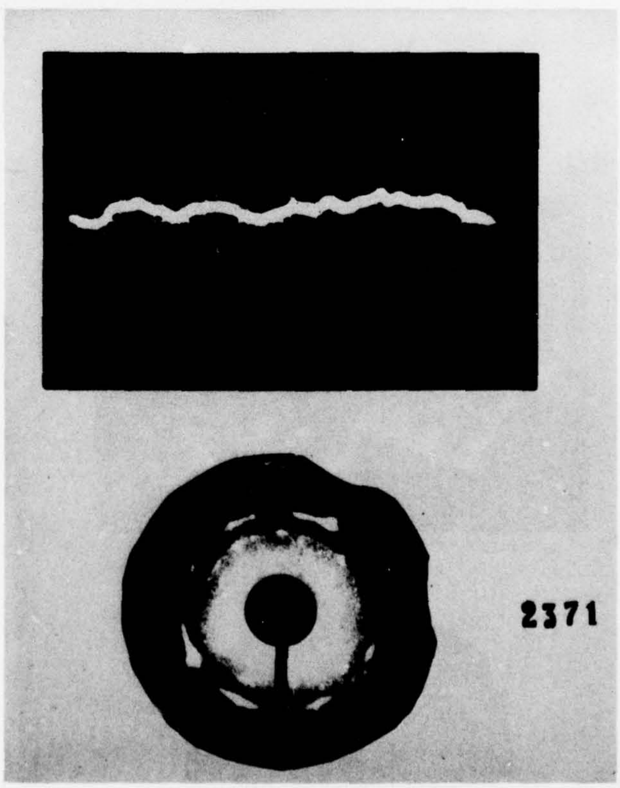


Figure 5

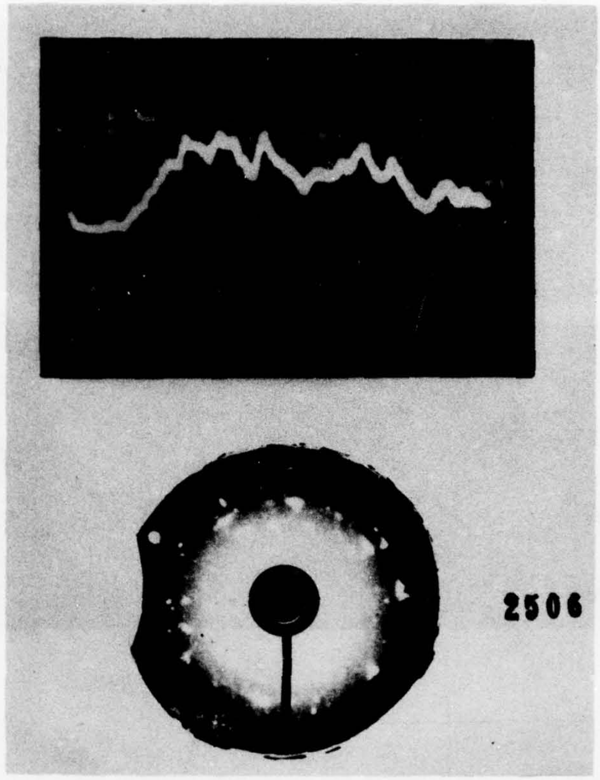


Figure 6

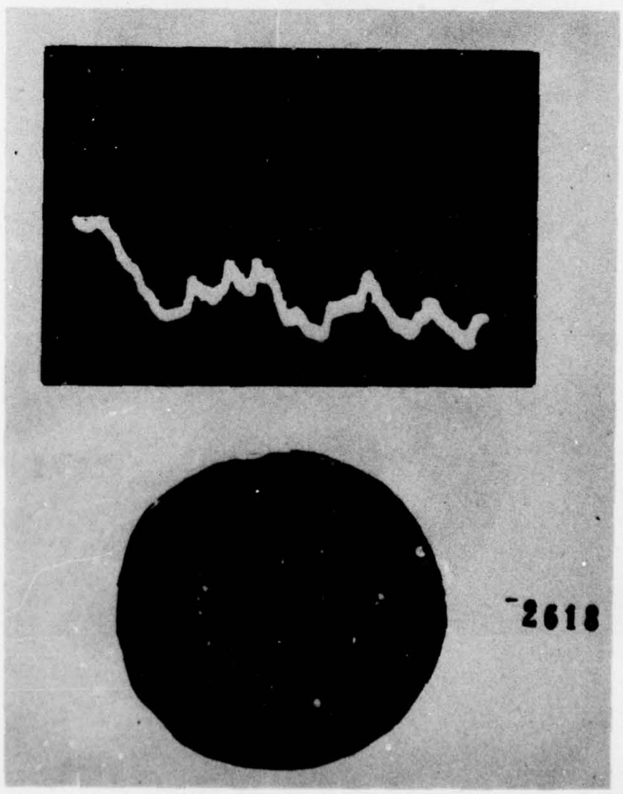


Figure 7

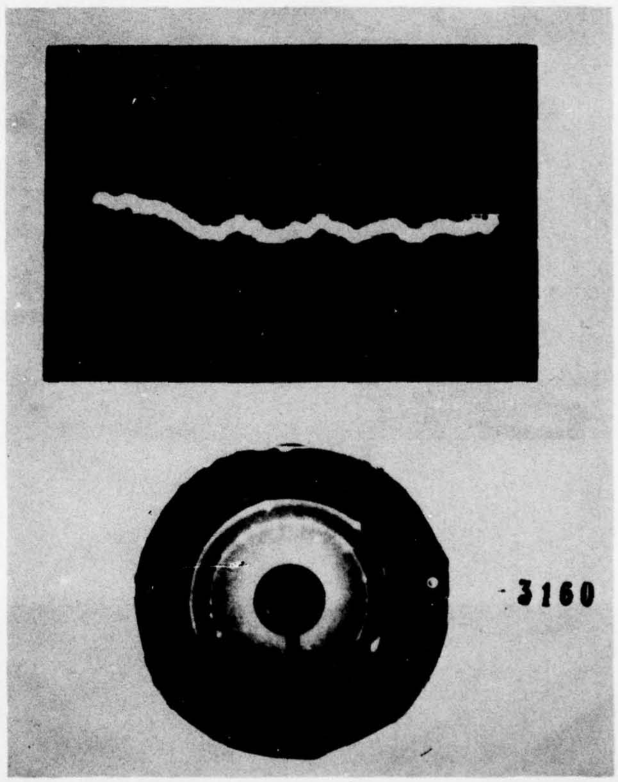


Figure 8

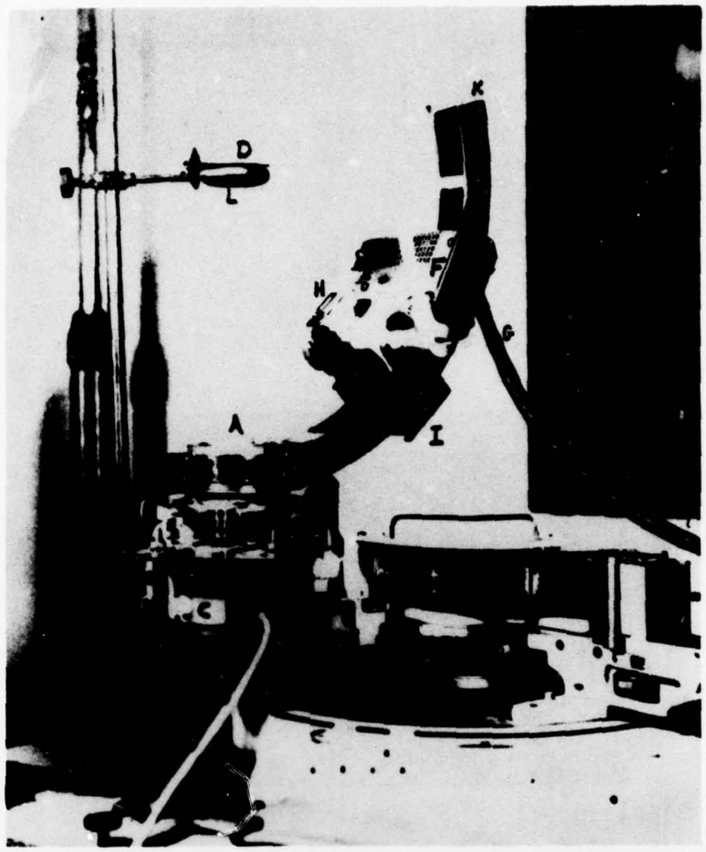


Figure 9(a)

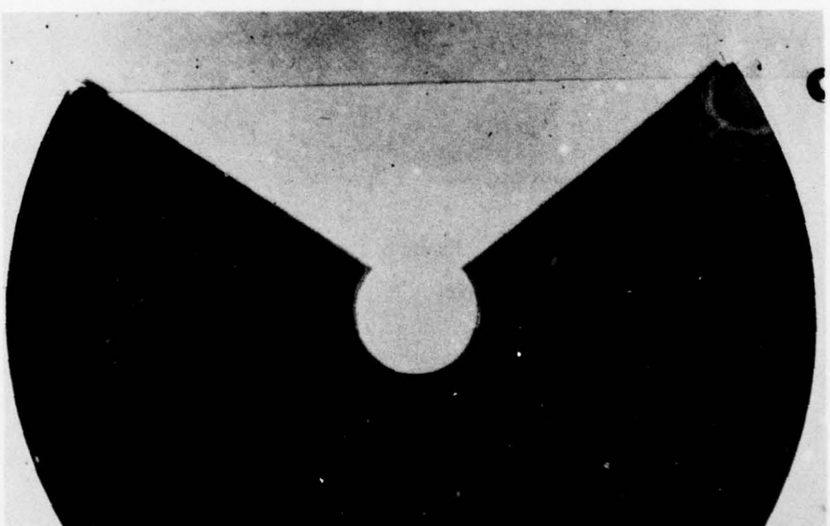
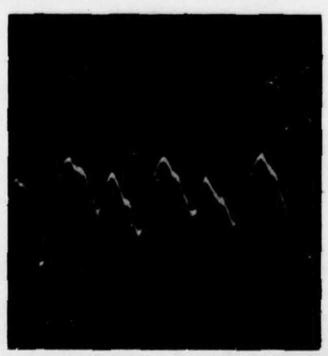


Figure 9(b)

2371 hours

2506 hours

2618 hours



3160 hours

Figure 10

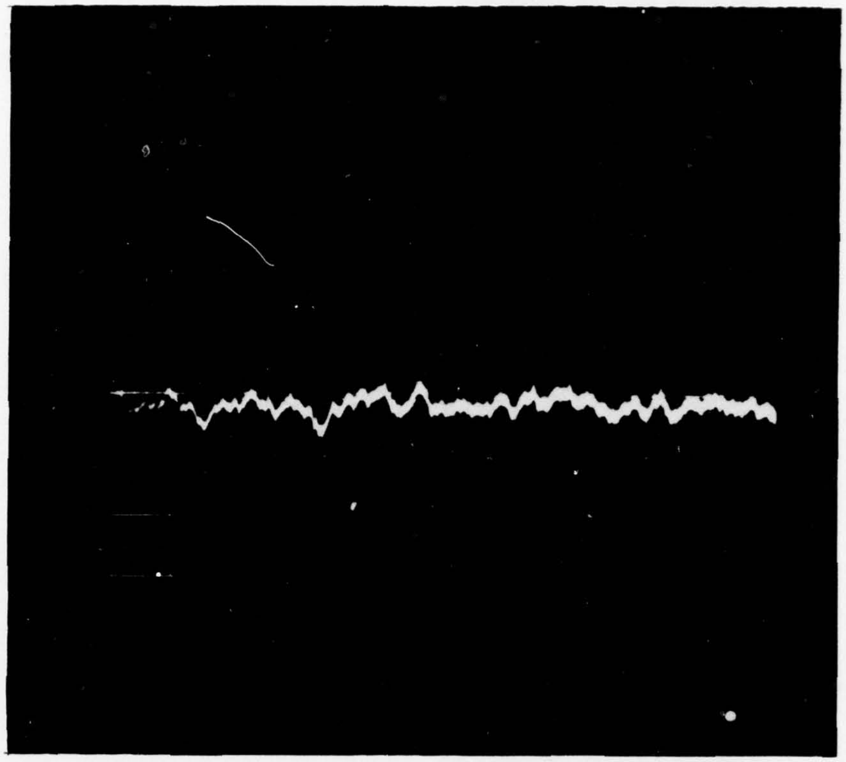


Figure 11

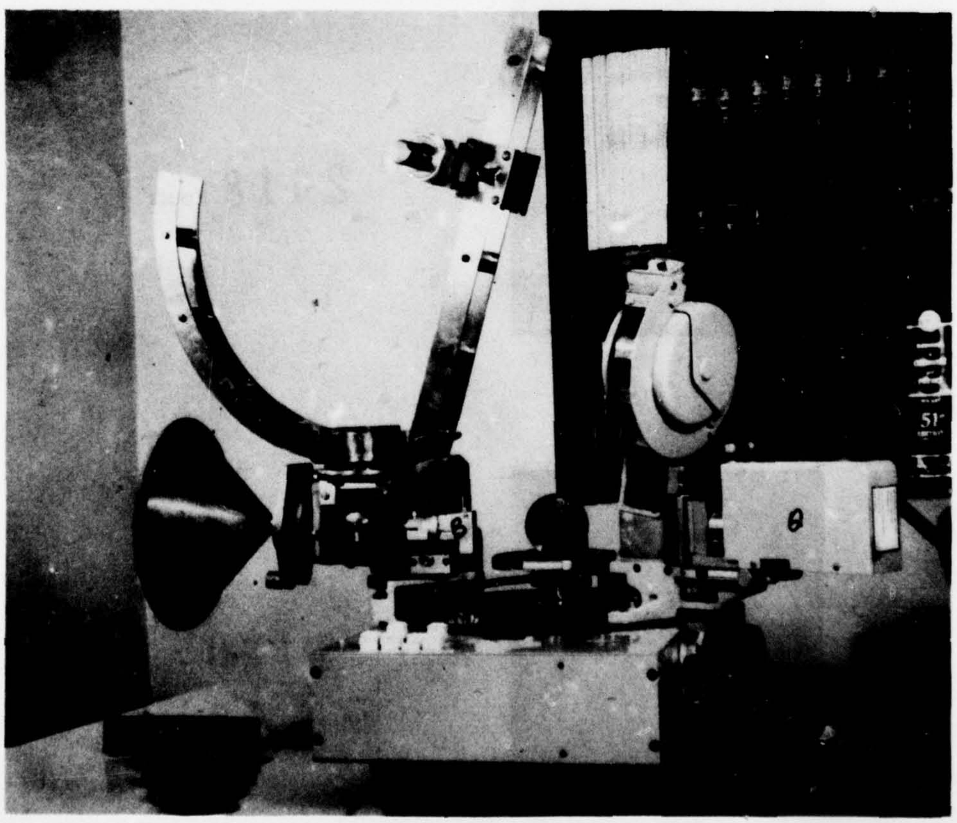


Figure 12

ON THE DETECTION AND MEASUREMENT OF CRACKS IN CRITICALLY LOADED HOLES

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Cracks in structures may originate from fastener holes. A method has therefore been developed for the inspection of the surface of a hole with the bolt removed.

For this inspection we use three types of instruments e g a stereomicroscope and a mirror in the hole, a surface roughness meter and an eddy current instrument.

With these instruments most types of defects may be indicated and evaluated.

The inspection starts with an examination of the surface of the hole with a stereomicroscope with built-in lightning. A mirror with its reflecting plane at 45° to the axis of the hole is introduced and rotated at increasing depths in the hole, fig 1. Despite the adverse angle of incidance of the light for the examination of the surface this method works satisfactorily with a trained inspector. Scratches, cracks, corrosion and fretting corrosion damages are easily observed, but it is difficult to estimate the depth of the defects.

However, the depth of scratches is measured with a surface roughness meter, Surtronic 3, which has been modified for this purpose. The pick-up which has an outside diameter of 6 mm is placed in an excentrically bored holder, the outer diameter of which is approximately 0,1 mm less than the diameter of the hole. A slot and a slight deformation make the holder function as a spring, pressing the measuring stylus against the surface of the hole, fig 2. The holder is made of brass and is covered with a nylon layer applied by powder coating in a fluidized bed unit. By turning the nylon layer the final diameter of the holder is obtained

By measuring circumferentially oriented scratches the normal motion of the surface roughness meter is used and the holder is connected to the meter by a flexible plaxtic tube.

Axially oriented scratches are measured by connecting the holder via a flexible spindle to a motor that rotates the holder at a speed of about one revolution per minute.

Scratches that have grown into cracks are indicated and measured with an eddy current technique. A Multitest EM 3300 with a memory cathode ray tube is used in combination with probes consisting of a coil mounted in the radial direction in a nylon bar. The coil has an outside diameter of 1,2 mm and is wound on a ferrite bar, 1,5 mm in length. The surface of the hole is scanned by rotating the probe at various depths in the hole or by giving it a spiral motion in the hole, fig 3.

Calibrations on fatique test specimens with cracks starting from a hole have shown that at the frequency used, 100 KHz, a linear relation is obtained between the eddy current indications and the depth of cracks up to 2 mm. In practice, spurious indications are obtained which limit the positve indication of cracks to a (minimum) depth of 0,2-0,3 mm. Corner cracks with an area of about 0,5 mm^2 are positively indicated.

In some types of holes a bushing is inserted to reduce the fretting between the bolt and the surface of the hole. A good interference fit is required and this implies that a steel bushing is preferred. Also, from the NDI point of view the material in the bushing must be carefully selected and the steel A286, a non magnetic and "hard to coldwork" steel has shown to be acceptable if a frequency of 10 KHz is used for the eddy current inspection. Insertion of a bushing with a wall thickness of 1 mm will rise the limit of detection with a factor of 2.

The use of bushings will of course preclude the possibility of visual inspection of the aluminium surface and in this case eddy current methods, ultrasonic methods, e g the Rotoscanner, and possibly radiographic inspection are the only applicable NDI techniques.

In holes without bushings, however, the use of the visual inspection, the surface roughness meter and the eddy current instrument constitute an inspection technique by the aid of which surface defects ranging from a few micrometers to several millimeters in depth can be detected and measured.

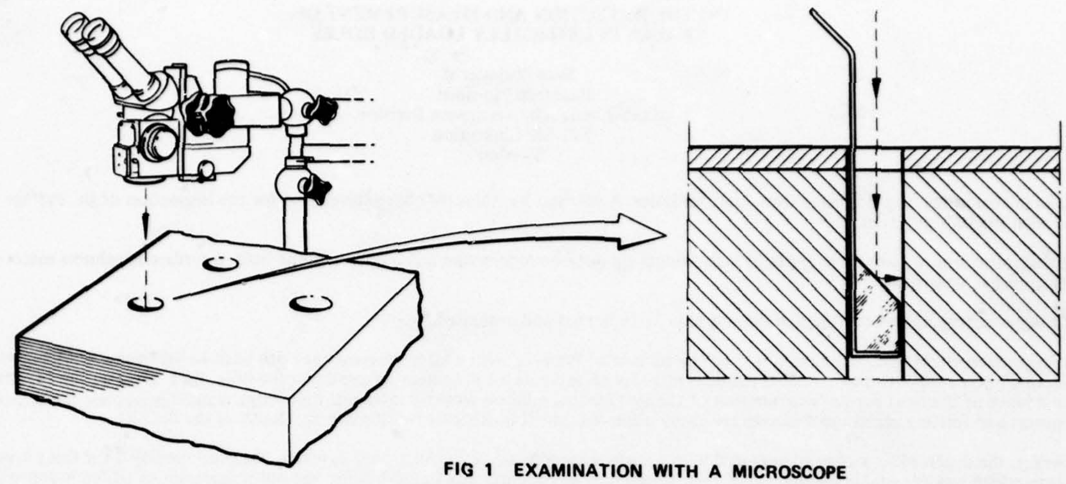

FIG 1 EXAMINATION WITH A MICROSCOPE

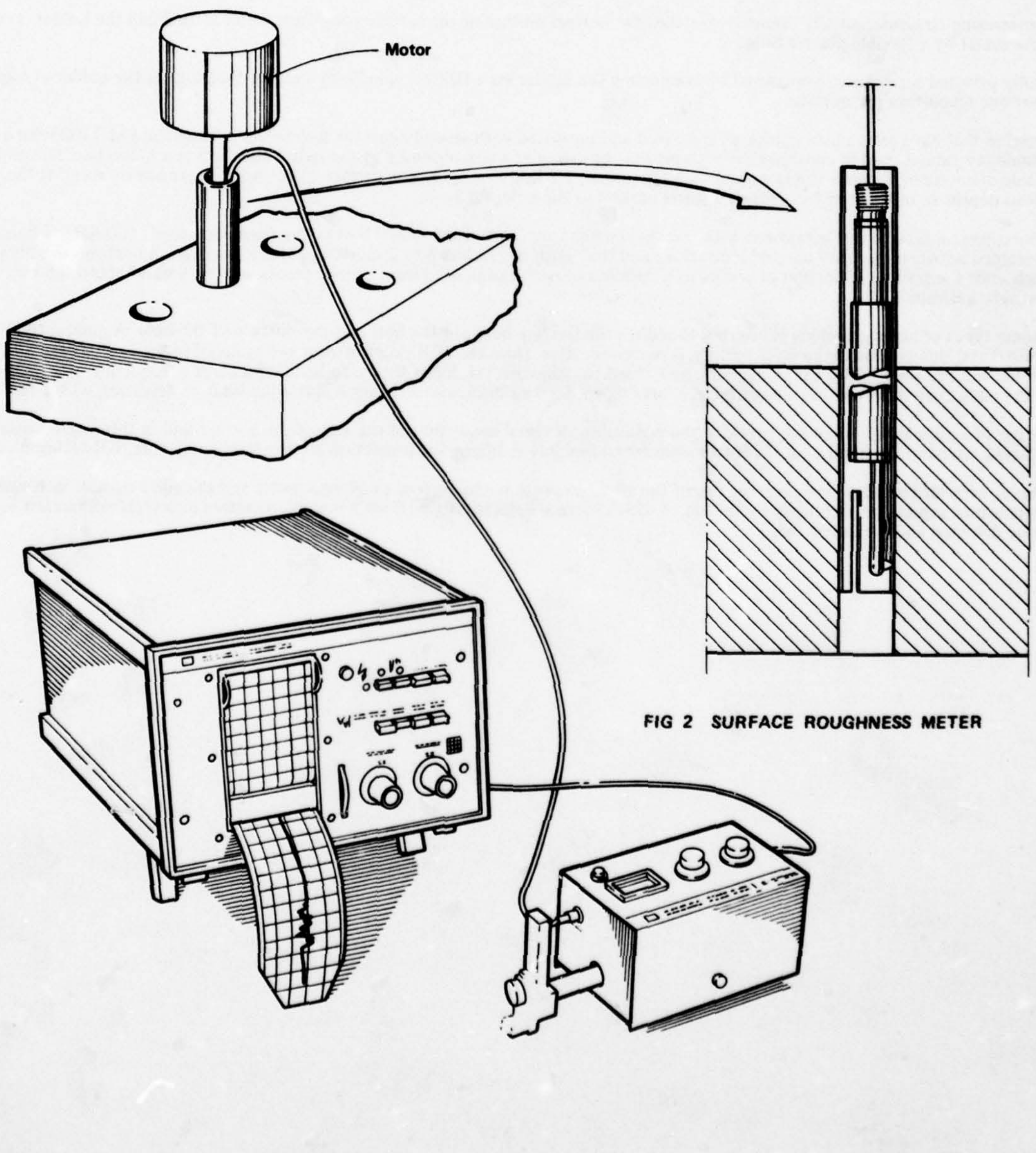

FIG 2 SURFACE ROUGHNESS METER

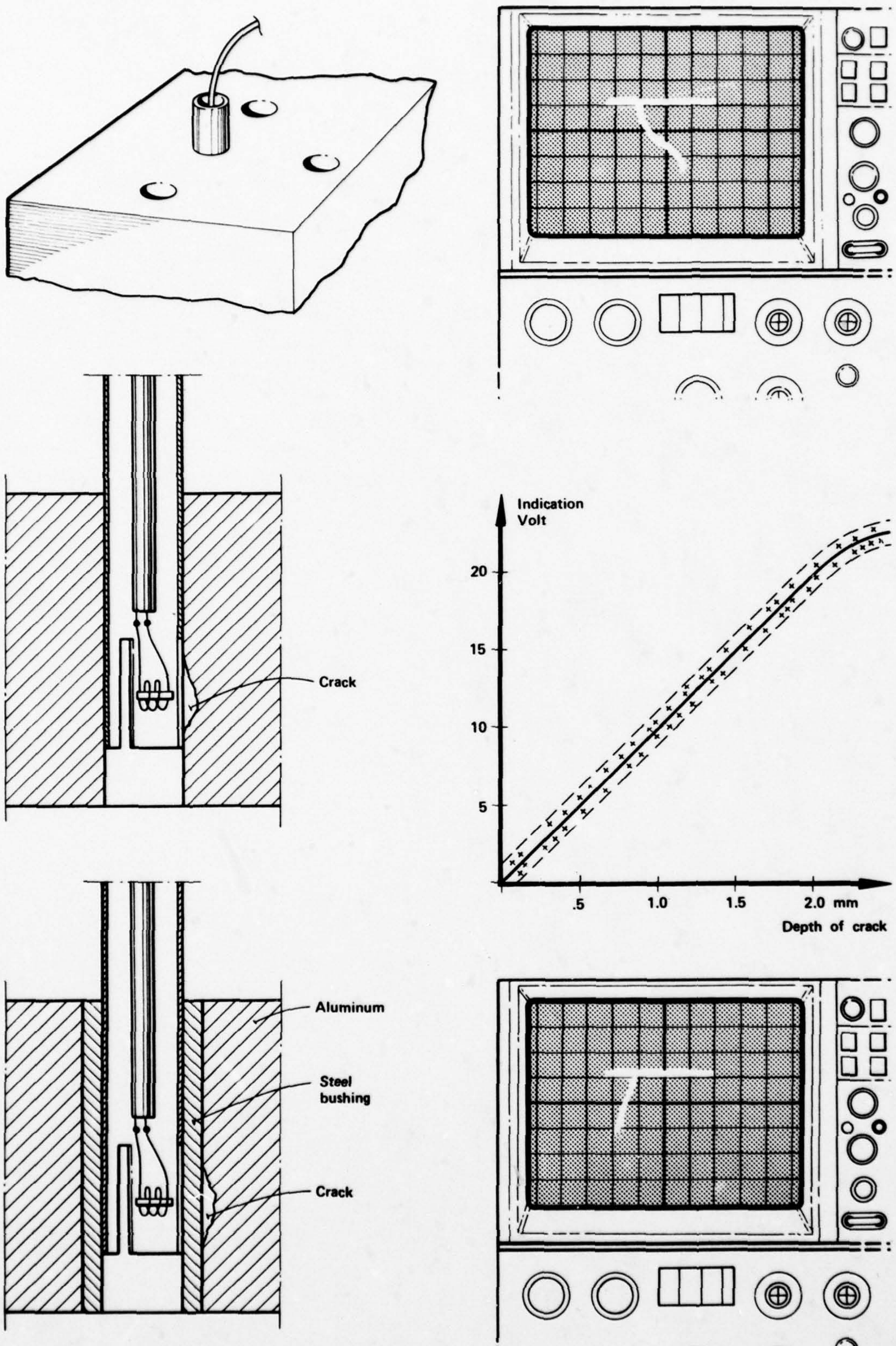

FIG 3 EDDY CURRENT

SESSION II
Part I: Techniques
Rapporteur's Report

by

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The four methods for non-destructive inspection that are the subject of this session can all be classed as "exotic" when seen from the eyes of the average NDI engineer. They, however, differ among themselves considerably in nature. When they could be classed as "exotic" that does not mean to say that they must be complicated or difficult either in principle or in application. A striking example of that is given by the method as presented by Dr H.Walther for measurement of sub-surface deterioration by means of relative magnetic susceptibility. The key for development of new non-destructive inspection methods in general is to find a parameter that can be measured rather easily but which has a close correlation with the material property to be measured. In the case as discussed it concerns steel super alloys, such as used in turbine blades, that may detrimentally change composition due to high operational temperatures. This is caused by oxidation and carburization in sub-surface layers. The method uses the phenomenon that this deterioration causes change in the ratio of ferro-magnetic constituents (Fe, Co and Ni) against non-ferro-magnetic constituents, such as chromium. By using a very sensitive magnetometer small local compositional changes can be measured. The method thus works at zero frequency and has low sensitivity for the quality of the contact. In its simplicity of principle and application this is an example of the ideal of the non-destructive testing engineer.

The method as described by Dr P.Pizzi, using small angle neutron scattering is, for the time being, only available to those of us who have a suitable neutron radiation source and the further rather sophisticated installation. However, also that method is able to measure anomalies *below* the surface to be inspected. It would be interesting to know where both methods overlap each other in capability and where application areas remain not accessible to both methods. A solution of these questions could possibly be a positive factor for the urgence of development of more readily available and mobile neutron radiation sources that have proven to be very useful for inspection of p.e. adhesively bonded and advanced composite structures.

The X-Ray diffraction technique as described by Dr D.Kirk is typical a method that makes an accurate analysis of the conditions of a component and from there predicts, what the residual stresses in the inside may be. This is done by measuring very small strains in the material from changes in the spacing in the crystal plains. By step-by-step etching away surface material and subsequent diffration measurements a rather complete picture of the original residual stress condition can be obtained. By this etching method attention must be paid to possible stress relieve in the material due to distortion after etching of an unrestrained component.

The method as presented by Lt Col. Dr A.Tronca is a useful addition to the method of X-Ray diffraction, as discussed before, as it uses a different way of presenting the inspection results. The complicated method of measurement of the intensities by means of a Geiger type counter is replaced by an instrument that presents on an oscilloscope the diffractions in circles with different radii.

Concluding, the wish is expressed that study of these inspection methods will reveal clearly where these sophisticated NDI methods fill gaps between or overlap existing NDI methods.

This session was completed by an initially non scheduled lecture by Mr S.Malmqvist, describing his experience with the detection of small fatigue cracks in critical loaded holes of 8 mm diameter. The effective method used rotating Eddy Current probes with very small coils at 100 kHz in combination with a memory cathode ray oscilloscope. During this lecture the crucial point of the influence of the human element in the reliability of the NDI end-result formed an important subject. That must be considered as one of the most important topics when now and in the near future more and more emphasis is placed on NDI for judgement of the reliability of important aerospace components.

DISCUSSION SUMMARY
Session II – Part 1

T.Gaymann (GE)

We have heard a very clear paper about x-ray diffraction from Dr Kirk. From the paper it seems that this is a very suitable method for determining residual stresses. Although the basis of the method has been known for some time and it has been improved recently, nevertheless it appears to be very rarely used, even in laboratories. I would like to have the difficulties and disadvantages of this method explained.

D.Kirk (UK)

I would agree in part with Dr Gaymann, since 99% of the residual stress measurements which are made are never published. I have seen only 50 or 60 papers dealing with this subject, although I have personally carried out over 300 investigations, each of which would correspond to a paper. This is also the case in many other companies, so the situation is like an iceberg and we are only seeing the tip of it.

There are a certain number of problems; if there were no problems, a lot more people would be using the technique. One of the problems is that the process is fairly expensive because it is time consuming, but there are a lot of developments taking place to speed up the measurements. For many years there has been a technique in America called "Fast Stress" and now the Japanese have brought out "Strain Flex". The Americans are also funding developments in various universities, but some of these will end up as white elephants. A lot of work is being done on the improvement of the equipment, and someone will eventually solve the mechanical problems involved in measuring the residual stresses rapidly.

P.Pizzi (IT)

With the technique of neutron scattering we improve our non-destructive investigations by an order of magnitude. This is very important because with the development of new materials and with the need to control very small flaws and their propagation, it is very necessary to have techniques of this type. Although there is the problem of requiring a nuclear reactor, we should remember that nuclear reactors exist and the real problem is to use them in the correct way. We should also remember that neutron generators are very small and not so expensive, and it should be possible to reduce the volume of the equipment required so that it will fit into a small room in the near future.

T.Sharples (UK)

Dr Kirk gave examples of very small values of residual stresses. These implied great accuracy of prediction, so I would ask him to speak about the tolerances implicit in his technique. It also surprised me that such small stresses were giving fatigue problems in service, since they were such a very small percentage of the ultimate strength of the material.

D.Kirk (UK)

The question of accuracy is perhaps the most important problem that I deal with. A lot of people have obtained erroneous results by not paying sufficient attention to detail. The technique depends fundamentally upon the lattice of the material; if one has a material with a sharp diffraction pattern such as aluminium alloy, then one can measure stresses with very great accuracy – about 100 lb/sq in. If on the other hand one has a hardened steel with a very broad diffraction line, then the corresponding accuracy approaches 500 lb/sq in. The accuracy is also a function of the geometry of the sample.

The questioner was surprised that failure occurred in service when the residual stresses at the surface were so low. The strength of a chain is its weakest link, and when a component is subjected to stresses fairly close to its fatigue strength then it will fail, even though the residual stresses are only a small fraction of the ultimate strength.

W.N.Reynolds (UK)

I have a question for Dr Pizzi. When using low angle neutron scattering, the defects we observe are much smaller than the critical size defects which one is worried about in structural testing or in service, when what one is observing is not an intensive defect but an extensive effect. The factor which one wants to relate to extensive changes, that is to say to massive changes of property, is the change in fracture toughness. I therefore wish to ask Dr Pizzi if any work has been done in relating the sort of changes which one can observe to the fracture toughness of the material.

I also wish to ask about the inspection of fibre reinforced composites. If you can observe low angle neutron scattering which is really characteristic of the fibre matrix boundary, and one is completely satisfied that the effect

of the fibres and the matrix have been eliminated, then we have a tool with which we may study the degeneration of composite materials under different environmental conditions which cause changes in the fibre/matrix bonding.

P.Pizzi (IT)

I agree with you that we obtain bulk volume information, and the average dimension is less than the critical dimension which would be useful for fracture mechanics. However, this is not true for all materials. For example in the case of ceramics (in particular silicon nitride) where the range of the very small dimension is in the order of microns, then this is a very useful technique.

My second point is that the method is not only dependent upon the defect but also on the structural deformation process. This is very important, because to my knowledge all non-destructive investigations to date have been orientated towards the detection of large cracks. They have not been concerned with the micro-structural degeneration process. This would be important if, for example, one is rejuvenating turbine blades by heat treatment and wishes to avoid a dangerous phase.

I have insufficient experience in the field of composites to deal with your second question. My presentation was directly concerned with an experiment performed two years ago and which was mainly orientated towards nickel super alloys and steels. I think, however, that this technique could give important information about composite materials, because the magnitude of the voids is of the order of 100 Angstrom, which is a useful range for neutrons.

W.N.Reynolds (UK)

Did you measure the change in fracture toughness with the change of the quantities that you can observe?

P.Pizzi (IT)

I have correlated the evolution of micro-structure to the residual life of the alloy, in other words I have correlated the diminution of the characteristics of the material indirectly by comparing, for example, creep experience with the micro-structural degeneration.

DYNAMIC NONDESTRUCTIVE TESTING OF MATERIALS

by
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SUMMARY

The result of our investigations show that "damping" or "internal friction" and frequency measurements can be employed for the study and detection of macroscopic defects as well asmicroscopic. For instance, flow detection and quality control can be made as well as the measurements of some physical properties.

The last decade has witnessed in the progress of nondestructive testing techniques that a gradual transformation has occured from macroscopic properties of materials. This extended the capabilities of nondestructive testing techniques to their ultimate limits. It is quite obvious that in the near future the damping properties of materials will carry much greater weight in the nondestructive technology.

I. INTRODUCTION

"Nondestructive testing" is a general name given to all test methods which permit testing or inspection of material without impairing its future usefulness. As Mc Master(1) defined, it is the art which includes all possible methods of detection or measurement of the properties or performance capabilities of materials, parts, aasemblies, structures, and machines, which do not damage or destroy their serviceability. Thewlis (2) made a more concise definition as the test which in a particular context will not damage the material being examined to such an extent or in such a fashion as to render it incapable of being used for the purpose for which it was originally intended. These definitions indicate that a given test may not be nondestructive in all circumstances.

From an industrial viewpoint, the purpose of nondestructive testing is to determine whether a material or part will satisfactorily perform its intended function. Absolute, perfect ,and sound industrial material does not exist. Any correctly applied nondestructive test can tell only whether the relative soundness of a specimen lies within specified tolerances.

The above definitidns indicate that nondestructive testing is far older than one usually thinks. Archimedes was one of the earliest investigators in NDT; around 200 B.C. he used the principle of flotation to determine whether a crown was made of gold. "Candling" of eggs is another nondestructive test method which was first used by the farmer.

One of the oldest nondestructive tests involves striking a specimen with a hammer and listening to the sound produced. This was presumably used by the ancients to check whether their baked clay pots and their glassbottles were sound. The existance of a flaw is indicated by an "off tone" ring and a rapid diminishing of sound intensity. This method is not too reliable, because the frequency of the sound emitted is somewhat dependent on the way the specimen is supported and the specimenis struck. This is the basic principle involved in damping measurements. The natural frequencies of some spemens may be beyond the audible range but this difficulty can be overcome by use of suitable electronic instruments. The rate at which the sound intensity of a vibrating specimen decreases is a characteristic of the condition of the material. The unaided human ear can determine differences as large as 20 % in the decay time. In recent years, the rate of attenuation of vibrations in solids has been the subject of many investigations. The attenuation measurements and the natural frequency tests are both nondestructive, because the vibration amplitudes are usually so small that the stresses produced in the specimen have no or a negligible effect on the material.

By the use of attenuation and frequency measurements, flaw detection and quality control can be made as well as the measurements of the elastic moduli, coefficents and activation energies of diffusion, distribution and concentration of point defects, size

size of clusters of foreign atoms, dislocation densities and velocities, loop length of dislocations, Peierls energy, energies of formation of dislocation kinks, etc. Some physical and metallurgical phenomena such as annealing and cold-working, plastic deformation, phase transformations, fatigue, effects of irradiation, ferromagnetism have also been investigated.

II. NATURAL VIBRATIONS

1. THEORY

Every specimen has certain characteristic frequencies at which it can be made to vibrate. Resonance may be defined as the excitation of a system by matching the frequency of an applied force to a characteristic frequency of the system. The characteristic frequencies are functions of the size, shape, mass, elastic properties and mode of vibration produced in the specimen. The natural frequencies can therefore be expressed as:

$$F = (\text{Shape factor}) \times (\text{Physical-constants factor}) \tag{1}$$

The shape factor includes length, width and thickness, and the physical constants factor consists of the modulus of elasticity, density, Poisson's ratio.

The above equation can be used for calculating the modulus of elasticity when the natural frequency of vibrations is determined.

A given sample can be made to vibrate in one of the following modes:

A. Flexural mode: This mode of vibrations is shown in Fig.1 .

B. Longitudinal mode: Fig.2 shows a bar vibrating in compression-tension or longitudinal mode with a single node at its geometric center.

The frequency equation for a rectangular bar of cross-section ($A = hxb$) which is vibrating longitudinally or flexurally is given by Mc Master (3) as,

$$f = (k^2/2\pi L^2)\sqrt{E\,I\,g / A\,p} \tag{2}$$

Where
- f= frequency,cps.
- k= a constant depending upon mode of vibration.
- L= length, cm.
- E= Young's modulus, Kg/cm^2.
- I= Moment of inertia, $b\,h^3 / 12$.
- g= acceleration due to gravity, cm/sec^2 .
- A= area of cross-section, cm^2 .
- p= density, Kg/cm^3 .

For a square bar Eq.(2) takes the form,

$$f = \frac{k^2\,h}{2\,\pi\,L^2}\sqrt{E\,g / 12\,p} \tag{3}$$

or collecting constants and using for k a value of 4.73 for the fundamental flexural mode of an unsupported bar,

$$f = \frac{20.3\,h}{L^2}\sqrt{E / p}$$

or

$$E = 0.00242\, f^2\, L^4\, p / h^2 \tag{4}$$

The wavelength (λ) of the fundamental longitudinal resonance frequency is related to the sample length (L) by,

$$\lambda = 2\,L \tag{5}$$

for fundamental flexural resonant frequency the above equation becomes,

$$\lambda = L / 2 \tag{6}$$

From any of the above equations thin-rod sonic velocity may be calculated. From Eq.(5) one obtains,

$$V_o = f\,\lambda = 2\,f\,L = \frac{40.6\,h}{L}\sqrt{E / p} \tag{7}$$

where V_o = the thin rod sonic velocity in cm/sec. Sound velocities may also be measured by ultrasonic techniques. In this case the "bulk" velocity (V_L) is measured which is given in cm/sec by,

$$V_L = 40.6 \; h \;/\; L \sqrt{(E \,/\, p)\;(1-\sigma)\;/\;(1+\sigma)(1-2\sigma)} \tag{8}$$

where σ = Poisson's ratio. It is seen that the ratio of the ultrasonic bulk velocity to the resonant thin-rod velocity is,

$$V_L/V_o = \sqrt{(1-\sigma)\;/\;(1+\sigma)(1-2\sigma)} = f(\sigma) \tag{9}$$

C. Torsional mode: A bar may vibrate in the twisting or torsional mode, as shown in Fig.3, with a single nodal plane at its center. The frequency equation (4) for this case is:

$$G = B\,W\,f^2 \tag{10}$$

Where
- f= torsional frquency
- G= shear modulus
- W= weight of the specimen
- $B = 4\;L\;R\;/\;g\;A\;i^2$
- L= specimen length
- A= cross-sectional area
- i= unity for first mode, two for second, etc.
- R= ratio of polar moment of inertia to the shape factor for torsional rigidity. The ratio R is unity for a circular cylinder and 1.183 for a prism of square section. For rectangular sections it is given by

$$R = (a/b + b/a)\;/\;(4a/b - 2.52(a/b)^2 + 0.21(a/b)^6) \tag{11}$$

Circular Plate:

a. A thin unsupported circular plate (disc) may vibrate in <u>flexure</u> in the <u>gravest</u> diametrical mode, shown in Fig.4 , with two nodal diameters crossing at right angles. Grinding wheels are tested for flaws and cracks by this technique Mc Master (3),and Bordoni et al (5) have investigated low temperature internal friction peak in circularly shaped Nb specimens.

b. Radial mode: A circular plate may vibrate in compression-tension in the <u>gravest</u> radial mode , shown in Fig.5, with a single node at its center.

For a circular plate, the general frequency equation is:

$$f = \frac{k}{2\,\pi\,r^2}\sqrt{g\,D\,/\,p\,h} \tag{12}$$

Where
- f= frequency, cps.
- $D = E\,h^3\,/\,12(1-\sigma^2)$ modulus of rigidity, Kg-cm.
- E= modulus of elasticity, Kg/cm^2.
- r= radius, cm.
- h= depth, cm.
- k= constant,depending upon mode of vibration.
- p= density, Kg/cm^3.
- σ= Poisson's ratio.

Solving the equation for frequency, using a value for k of 5.25 for the two-nodal diameter mode , gives

$$f = \frac{4.74\;h}{r^2}\sqrt{E\,/\,(1-\sigma^2)\;p}$$

or

$$E = 0.0445\;f^2\;r^4\;p\;(\;1-\sigma^2\;)\;/\;h^2 \tag{13}$$

c. Circular plate with axial hole: A special case is the circular plate with an axial hole, such as an abrasive wheel, as shown in Fig.6 . A correction factor has been developed for the two-nodal diameter mode which involves the hole radius (R) and the plate radius (r) as $(1 - (R/r)^2)$. With this factor applied the frequency equation for

the two-nodal diameter mode of the plate takes the form,

$$f = \frac{4.74\ h\ (r^2-R^2)}{r^4}\sqrt{E\ /\ p(1-\sigma^2)} \tag{14}$$

2. INSTRUMENTATION AND APPLICATIONS OF NATURAL VIBRATIONS.

a. Applications:

Dynamic testing is a non-destructive testing method by which the physical properties of certain materials may be assessed or predicted from an evaluation of the resonant frequency of vibration of a sample. There are many examples of resonance in daily life. Perhaps the most remarkable is the tuning of a radio or television receiver, making the set respond only to the electromagnetic wave for which it is tuned permitting amplification to an audible level .

When suitably set up for dynamic testing, most specimens of material will, as a rule exhibit resonance in the sonic frequency range, i.e. below 20 000 Hz. From the knowledge of the dimensions, the density, and the resonant frequency, the appropriate modulus may be calculated. There is a direct relationship between the resonant frequency and the tensile strength of the material, which may be a forging or a casting (as in the case of a crankshaft). In cast iron the strength depends on the percentage of flake or, as the case may be, nodular graphite. By comparing the object with a known reference it is therefore possible to confirm extremely quickly whether subsequent production of the same shape or form and dimensions equals the reference standard. In other words this method may also be used as a " Go - No go " selector.

The acoustic resonance vibration tests have so far been applied to the measurement of the following physical quantities such as:

1. Length, width, thickness, diameter.
2. Modulus of elasticity (E)
3. Shear modulus (G)
4. Poisson's ratio (σ)
5. Density (p)
6. Modulus of rupture
7. Damping capacity
8. Flaws or other inhomogeneities
9. Precipitation
10. Order-disorder transformations, phase transformations
11. Magnetism
12. Effects of alloying
13. Cold working and texture
14. Temperature dependence of E, G, , Modulus of rupture, Damping capacity.

Items 1,2,3,4 and 5 can be calculated through the frequency equations as explained in the previous section. Items 6,8,9,10,11,12,and 13 can be investigated by observing the changes of the elastic modulus (6). The temperature dependence data of the dynamic elastic modulus can be used directly for strength calculations of structures operating at elevated and reduced temperatures, and the inflections and other anomalies observed in E(T) make it possible to find with high accuracy the temperature at the beginning and the end of processes such as recrystallization, graphitization, quenching and tempering, precipitation hardening, plastic deformation, strain aging and recovery.

In the Aston University (97) the changes that occur in the characteristic frequencies have been employed as a means of nuclear reactor control . The internal temperature of a nuclear reactor has been measured up to almost 2000°C with about 2°C uncertainty. Changes in temperature could be closely followed through the changes in the characteristic frequencies. Although this approach may not have the precision of other methods, it has other advantages. First a wider range of materials can be considered for use, and noise due to radiation effects on electrically conducting elements is avoided. Furthermore, by using reasonably high frequencies ($\sim$100 KHz) and modest band widths, interference from mechanical noise is reduced. In the same laboratories studies of vibration modes of thick cylinders have been applied to the problem of detecting flaws in large blocks of carbon. Here the interested potential users are people who operate arc furnaces for steel smelting, using cylinders 60 cm in diameter. Flaws in these lead to costly furnace shutdown, thus any reliable nondestructive testing method would be welcome. By excitation of several different oscillation modes and with observation of both resonant frequencies and damping coefficients this has been possible.

Elastic moduli have been measured by the resonance vibration method in an extensive number of materials, e.g. in spring materials such as Aluminium, Tin-Phosphorus, Silicon -Manganese, Tin-Zinc bronzes and also in stainless steel and 48 % Zn-brass (7) .

The effect of porosity on the modulus of an otherwise homogeneous material has been the subject of a number of theoretical and experimental investigations. An extensive bibliography avilable on this subject shows that the effective modulus of a porous material is related to the shape and distribution of porosity in addition to the total void fraction (89, 90, 91, 92) .

Marlowe and Wilder (93) have studied sintering kinetics of powder metals through the changes in resonant frequency of a bar during sintering. Brockelman (94) correlated tensile strength, pore shape and orientation with thin-rod sonic velocity or the ultrasonic velocity of sintered materials. As illustrated by Fig.7,8 the sintered density is inadequate as a criterion of powder metal quality but velocity of sound propagation is a better measure (as for the strength of the material). Brockelman (94) reports that nonuniformities which probably originate during the pressing process affect appreciably the resonant frequency of prealloyed steel powder specimens thus presenting a method of detection.

Precipitation processes have been studied in many alloy systems such as Al-Cu, Al-Ag, Al-Zn, Al-Mg, Au-Ni by elastic modulus measurements. Fig.9 shows the results of the work of Tanaka et al (8) on Al-Ag alloy specimens. Aging occurs in two stages in this alloy, corresponding to the first and second stages of hardening. Below 200°C aging causes first a decrease and then an increase in the modulus. In the first stage Guinier-Preston zones are formed, while in the second stage an Al_2Ag phase precipitates which is coherent with the lattice . At temperatures above 210°C the G-P zones are unstable and the modulus increases with the precipitation of the Al_2Ag phase.

Effect of order-disorder transitions on Young's Modulus is seen in Fig.10. The upper curve illustrates the effect in Cu-Zn (beta brass) and Mg_3Cd, whereas the lower curve shows the effect as observed in Cu_3Au, Cu_3Pd, Ni_3Fe and Ni_3Mn . The longe-range order decreases with temperature up to the Curie point, T_c, above which complete disorder exists.

If a tensile stress is applied to an unmagnetized ferromagnetic solid, its length increases as a result of two effects : (a) elastic expansion, and (b) expansion due to magnetostriction, i.e., expansion resulting from the orientation of magnetization under stress. Magnetostriction causes the Young's modulus to depend both on the strain amplitude and the intensity of magnetization; this is illustrated schematically in Fig.11 (9).

Some phase transformations have been investigated through the variation of elastic constants . Fine et al (10) made a systematic study of the phase transformations in Chromium by this technique. Phase changes of second degree were observed by them at 37 and -152°C . At 37°C a sharp dip occured in the modulus vs. temperature curve (Fig.12). Measurements of other properties showed no indication of this phenomenon . It is suspected that at 37°C an electronic rearrangement occurs since no hysteresis is observed.

The effect of alloying in the dilute and finite concentration ranges is of some importance to the theory of alloys. Bradfield and Pursey's (11) investigations of Young's modulus is slightly smaller than expected (Fig.13) . This effect disappears with careful annealing and is attributed to the relaxation of weakly pinned dislocations in the nearly pure material. Annealing reduces the dislocation density or causes a more complete segregation of solute atoms along dislocations.

Elastic moduli decrease with introduction of small amounts of cold work. This effect makes it possible to study the cold working of metals by modulus measurements. Granato and Lücke's (12) theory predicts frequency, strain amplitude, and dislocation loop length dependence of elastic moduli.

b. Instrumentation used in vibration tests :

For excitation of longitudinal and flexural vibrations in the samples, different types of test setups have been developed. Such apparatus usually consists of a vibrator and a pick up, which in some cases may be combined together. The vibrator induces vibrations in the specimen and the pick up detects them, thus making it possible to measure the vibrations or their damping in the specimen (13). Grandchamp's (14) apparatus, as seen in Figs.14 and 15, operates on the principle of electrostatic excitation and detection. This assembly cuts the excitation when the vibration amplitude is above the top

level, counts the oscillations falling between the two levels during the damped vibration, and resets the excitation when the measurement is finished. The system of Fig.15 is now being manufactured by mass production (15).

Hasiguti et al's (16) apparatus is seen in Fig.16 which was used in the determination of concentration of point defects, dislocation densities and crystal structure in Uranium , Uranium dioxide and Zr-alloys.

Dr. Förster (17,18) designed and produced the instrument of Figs.17 and 18. This instrument can record semiautomatically the Young's modulus, shear modulus of any material which can be excited mechanically to vibrate . In Fig.17 when the switch S is moved to position 1 the excitation is by the oscillator. In position 2 of the switch S self-excitation takes place through the feedback, and the amplitude of the self-excited oscillation is kept constant by means of a control system. Resonant frequency can be recorded continuously as afunction of time and temperature by means of low temperature (for measurements down to $-200^{\circ}C$) and high temperature (for measurements up to $1000^{\circ}C$) attachments.

In Fig.19 an automatic system is seen that was developed in METU (19) . The most advantageous feature of this system is the self excitation loop which completely eliminated the need for an oscillator. Measurements are made and recorded automatically. Most of the units of the system are instruments commonly found in laboratories. Units such as VGA, peak detector and phase shifter can be built easily and at low cost.

Elastic constant and damping spectrometers developed by Beaton (20) ,Shaknazarov and Naskidashvili (21) , Thompson and Glass (22) have employed sophisticated servo mechanisms for purposes such as automatic adjustment of the air gaps between the transducers and the specimen and adjustment of the oscillator frequency. In the system shown in Fig.19 these problems have simply been solved by using support columns made of the same material as the sample and by the feed-back loop respectively.

Although the ultrasonic velocity can be measured,according to Eq.(8), by an Elastomat type instrument it is also possible to make the same measurement by pulse-echo technique (94) . Longitudinal ultrasonic velocity measurements are very capable of detecting the orientation and the shape of the porosity as well as the isotropy of the sintered materials. Brockelman (94) noticed that there existed a considerable difference between the longitudinal ultrasonic velocities measured in a direction parallel to pressing and perpendicular to pressing (Figs.20 and 21) due to the simple fact realized from microstructures (95). When the porosity assumed spherical shape after prolonged sintering this difference diminished.

Ultrasonic velocity measurements have proven to be very efficient means to detect and locate property variations such as the density in powdered metals. Hence they can be used for determination of density distributions.

Torsion Pendulum:

Different types of torsion pendulums were so far used by many investigators of torsional oscillations and shear modulus. In the Ké (23) types a biasing stress is applied on the wire sample. The inverted type pendulums as seen in Fig.22 completely eliminate the static loading of the sample. Inverted pendulums have also been automated by many researchers. Smith et al (24), Bays and Grandchamp (25), Miszenti (26) have designed special optical systems for automation of their pendulums and recorded the data either digitally on telex tapes or graphically. Harbottle's (27) special pendulum for investigations of neutron irradiated foils in the temperature range 77 - $300^{\circ}K$ is also worth mentioning. By means of this apparatus the amplitude of oscillations were maintained constant automatically, and data were recorded continuously.

A commercial type of pendulum is produced in Holland by Nonius (28) . This pendulum has been designed for testing of polymers (29) between the temperatures $-160^{\circ}C$ and $200^{\circ}C$ at 0.3 - 3 Hz frequencies. The decay of vibrations is recorded by electric sparkover between a needle and a rotating drum provided with special conducting paper.

3. TESTING OF CONCRETE.

Standard beams of concrete (20x4x4 in. or 28x6x6 in.) have been tested by the resonance vibration method (30) in the longitudinal, flexural (31, 32,33, 34) or torsional modes. As a vibrator an electrodynamic vibration generator is used, while a piezo electric crystal is used as pick-up. Positions of vibrator and pick-up and displacements in har-

monics are seen in Fig.23.

In Fig.24 a concrete beam is seen which is being tested in the longitudinal mode. Vibrations are induced by means of a variable frequency-oscillator which supplies electrical oscillations to the moving coil of the vibrator. The magnitude of the vibratory force applied to the beam is of the order of 1 lb. Moving coil vibrators are most suitable for exciting concrete beams and require afew watts input. The moving-coil part of the vibrator is usually brought out to a tapped plunger so that an extension piece fitted into this plunger can be attached to one face of the specimen.The magnet portion of the vibrator is supported independently of the moving-coil so as to allow the coil to move axially between the poles of the magnet without restraint. An alternative way to drive specimen is to terminate the moving-coil in a circular plate which is placed near but not touching the face of the specimen. The vibrations are transmitted through the airgap so that there is no mass loading on the specimen.

The pick-up can be:

i. A crystal accelerometer which is light enough to be stuck to the beam or which can be supported independently of the specimen but be held in contact by a weak adhesive.

ii. A gramophone pick-up in which the needle rests on the specimen and responds to vibratory displacements in a lateral direction.

iii. An electromagnetic pick-up of the telephone earpiece type in which a thin disk of soft iron or stalloy is fixed to the specimen and the magnetic pick-up is held close to but not touching this disk.

In relatively lighter beams stalloy disks may be stuck to the ends which may be vibrated by generating direct and alternating magnetic fields. At the pick-up end the vibrating disk produces electrical oscillations in the coil of a small electric magnet.

The search pick-up is switched to the amplifier after the frequency has been tuned to resonance, and the nodes and antinodes of vibration are found according to whether there is a maximum or minimum deflection on the output-meter when the search pick-up is moved along the specimen. The positions of the nodes and antinodes enable a check to be made on the type of vibration excited in the specimen and the order of the harmonic of the response.

In the longitudinal mode of vibrations the dynamic modulus of concrete beams have been calculated by,

$$E = 4\,(n_L)_i^2\,L^2\,p\,/\,g \tag{15}$$

Where $(n_L)_i$ = longitudinal resonance frequency of the i'th harmonic
L = the length
p = density
g = gravitational acceleration.

This equation holds for beams which are very long in relation to their cross-section. Otherwise a correction factor has to be applied (35) which can be determined from Fig.25.

For flexural resonance the following equation is used:

$$E = 4\,\pi^2\,L^3\,W\,(n_f)_i^2\,T_i\,/\,g\,I\,K_i^4 \tag{16}$$

for beams and cylinders, where I is the moment of inertia of the cross-section,W is the weight, K_i is a factor which for the first six resonant frequencies has the following values: K_1=4.730, K_2= 7.853, K_3= 10.996, K_4= 14.137, K_5= 17.279, K_6= 20.42 . For a beam of rectangular cross-section the same equation becomes,

$$E\,/\,p = 48\,\pi^2\,L^4\,(n_f)_i^2\,T_i\,/\,g\,a^2\,K_i^4 \tag{17}$$

Where a is the thickness and T_i is a correction factor for the ith harmonic which can be obtained from Fig.26 .

The dynamic shear modulus of elasticity can be drived for concrete beams of any cross-section by the relation (10).

The resonance vibration method of determination of Young's Modulus permits reproducibility of results and thus fewer experiments are necessary. The following effects on Young's modulus of concrete were investigated by resonance methods: effect of size of

specimen and test frequency, effect of age and curing conditions , effect of anisotropy (double hump in the resonance curve), effect of composition. Also the relaxation between the static and dynamic moduli (36), relations between the dynamic modulus and the strength (37, 38, 39, 40, 41) have been investigated by various researchers.

Kessler and Higuchi (40) have obtained the compressive strength of concrete by determination of the modulus of elasticity and the resonance curve. Fig.27 shows a schematic diagram of their apparatus. Specimens were 15 by 30 cm cylinders. The accuracy of prediction was within 5 % and was obtained without knowledge of the age ,mix ,or moisture content of concrete. Between 1940 and 1951 many investigations were made in USA which employed the flexural resonance method as a criterion for assessing the durability of concreteexposed to cycles of freezing and thawing. As a consequence of this work ASTM standards C.290, C.291, C.292, and C.310 were formulated in 1952, 1953 and 1956 specifying the flexural resonance method (C.215) as the means of following deterioration. Also British Standard 1881 makes the dynamic testing of concrete mandatory. Daxelhoffer (42) and Batchelder and Lewis (43) have also used longitudinal and torsional resonance in freezing and thawing investigations. It was reported that (44) sixteen out of thirty-one laboratories used resonance methods for assessing durability : at least ten of these employed the flexural resonance method. It is also known that (30) damping coefficient measurements provide a more sensitive indication of deterioration than the dynamic modulus. In South Africa (45) corrosion of concrete sewage pipes were investigated by resonance methods. The daily quality control in the manufacture of cement was also made in Japan (46) through the correlation between strength and dynamic modulus during the aging of concrete. Resonance experiments have also been employed to obtain data on the elastic properties of Bituminous materials to follow the progressive changes due to accelerated weathering (47). Voskuil and Van Os (48) have suggested this technique as a method of quality control and sorting of refractoy materials such as bricks into their different grades. Davies and Clements (49) have also claimed that damping measurements are sensitive indications of quality of bricks and ceramic materials. Glass has been tested by resonance methods for many years; the dynamic modulus was shown to be sensitive to the constituents of glass (50).

Elastic properties of rocks have been determined by resonance methods which were found to be of interest to seismologists, for classification of aggregates (51) and also in specific engineering work as, for example, in the construction of a dam.

III. DAMPING PHENOMENA (DAMPING TESTS)

1. INTRODUCTION

Even when isolated in vacuum, the amplitude of a freely vibrating body will decrese with time. This phenomena is called "damping " or "internal friction" . Without making any assumptions about the nature of internal friction the following general definition may be given:

$$Q^{-1} = \Delta W / 2 \pi W \tag{18}$$

Where ΔW= the energy dissipated in taking a specimen through stress cycle and W= the elastic energy stored in the specimen when the strain is a maximum.

Damping measurements are becoming more and more common in research laboratories because they are highly sensitive to small concentration and phase changes in solids,above all in metals and alloys. By measuring damping it is often possible to form an opinion about the parameters of a dislocation structure, the features of metallographic structure, and changes in the concentration and location of point defects. Such processes as the precipitation and dissolving of surplus phases, recrystallization, relief annealing, quenching and tempering, precipitation hardening, plastic deformation, strain aging and recovery are successfully studied by the internal friction method. This method is closely associated with the change in a material's magnetic properties and also with oxidation, agglomeration, and internal adsorption of impurities in crystal lattice defects.

2. TECHNIQUES

Damping or internal friction in solids may be produced by several different mechanisms (52). Here a review of some of the techniques that have so far been used for investigating internal friction will be worthwhile.

a. Determination of the resonance curve during forced vibration: In this technique the frequency is changed and the two frequencies f_1 and f_2 for which the amplitude is

$1/\sqrt{2}$ of the value at resonance are found. Then internal friction is given by,

$$Q^{-1} = (f_2 - f_1) / f_r \tag{19}$$

If the square of the amplitude is plotted against frequency then,

$$Q^{-1} = (f'_2 - f'_1) / \sqrt{3}\, f_r \tag{20}$$

Where f'_1 and f'_2 are the frequencies at which the ordinates are one half the maximum value (Fig.28). It is advisable to employ the resonance method when damping is high, for instance on the high temperature side of the internal friction background.

b. Determination of the amplitude decay in free vibrations: The time (Δt) for the amplitude to decrease from its initial value G_i to G_i / e is determined (Fig.29) . The number of cycles of vibration that have occured within the time interval Δt is found by,

$$n = \Delta t \cdot f_r \tag{21}$$

Then internal friction can be given as,

$$Q^{-1} = 1 / n\pi \tag{22}$$

If one defines the natural logarithm of the ratio between the amplitudes of successive free oscillations to be the logarithmic decrement δ, then

$$Q^{-1} = \delta / \pi \tag{23}$$

c. Determination of energy absorption: The specimen is oscillated at a constant amplitude of the exciting force according to,

$$Q^{-1} = F / A I w_r^2 \tag{24}$$

Where A= the oscillation amplitude
F= the amplitude of the exciting force
I= the moment of inertia
w_r= the resonant frequency.

Internal friction can be recorded by using this principle as shown in Fig.19 .

d. Determination of sound wave propagation constants: In this group of techniques the propagation of sound waves is observed directly by using pulses or by interferometric means by using standing waves. The amplitude of a progressive wave will decrease with distance traversed as it passes through a solid medium. If the amplitude decay is expressed as

$$A_x = A_o \exp(-Cx) \tag{25}$$

then C is the attenuation coefficient per unit length . A more fundamental quantity is μ, the attenuation per wavelength (λ) of the wave, i.e. per cycle on the time scale. It is easily shown that $\mu = C\lambda = \delta$. These methods are the most suitable for very high frequencies, but they are limited to low stress levels.

3. APPLICATIONS AND APPARATUS FOR DAMPING

As it is mentioned in the beginning of this section, many different material properties have been determined by the use of internal friction techniques. The works of Wert (53,54) ,Polyakov (55) ,Pavlov (56) and Stanley (57) constitute typical examples to the determination of diffusion energies and diffusion coefficients. Wert (53,54) determined the diffusivities and diffusion energies of interstitials in V, Cr, Fe, Nb, Mo, Ta, W by a torsional pendulum from the Snoek effect. Polyakov (55) used the same method to determine the coefficient and energy of diffusion of carbon in Fe-Mn and Fe-Mo alloys.

Boone and Wert (58), Polyakov (55), Szkopiak (59), Inokuti et al (60), Buck et al (61) determined the concentration of interstitials such as O, C, H, N in Nb and Fe by internal friction. Here the following principle is used: The height of the damping is proportional to the interstitials in solution. When some solute atoms precipitate as in aging, the peak height falls,implying that concentration of solute atoms that contribute to damping decrease. Hence these measurements can also be used for the study of the aging process (62). These studies constitute typical examples of the use of internal friction as a nondestructive chemical analysis technique (Fig.30).

The effect of grain size on the internal friction have been studied for various metals(Figs. 31, 32, 33). Fig.31 demonstrates the effect of grain size on the damping of Zr (63). Measurements reported by various authors indicated that damping depends on the square of the average grain size. Leak (64) showed that the relaxation in Fe specimens of different grain sizes can be approximately written in the form:

$$\tau = \tau_o \, d^2 \exp \left(Q_f / R T \right) \tag{26}$$

Where Q_f is the activation energy of grain-boundary damping (Fig.32). The pre-exponential frequency factor (τ_o) tended to lower values as the grain size decreased (64,65). Various authors (63,65,66)report that the grain boundary damping peak is absent above a certain grain size (0.4 μm for Fe - 0.04 wt %C alloy, Fig.33,and 0.75 mm for Ni).

Roman et al (88) determined the grain size in nuclear fuel elements cast from *Uranium-Chromium* alloys by ultrasonic attenuation measurements. They correlated the mean grain diameter which was in the range 50 to 200 μm with the attenuation coefficient for three ultrasonic frequencies 4, 6, and 12 MHz . Results were claimed to be in good agreement with the theory and the metallographic determinations.

Phase transformations and aging in Al-Cu, Al-Ag, Al-Zn, Au-Ni, etc. alloys have been studied using the damping technique. Phenomena such as the decay of quenched in vacancies, the *formation* of *Guinier-Preston Zone*-1 and *Guinier-Preston Zone*-2 in its early stages, the reversion of G.P. -1, the appearance of θ', and the transition from θ' to θ could all be followed. The technique could be applied to more complex alloys.

Fig.34 illustrates the changes in the θ' peak developed in an Al-Cu (4 wt %) alloy (62). θ' precipitates when this alloy is aged between 200^o and 290^{o}C and produces a peak the height of which is proportional to amount of θ'. Along with the rise of the θ' peak, the background damping level rises due to the formation of incoherent θ ($CuAl_2$) precipitates from θ'. Progressive rise of the background can be interpreted as an increase of the area of the incoherent boundaries of θ precipitates.

Mishek and Toman (67) studied the aging in Al-Ag alloys by damping measurements. It is very well known that at low temperatures aging is a two stage process; first Guinier-Preston Zones are formed, then the second phase precipitates out. At high temperatures aging is a one-stage process; after a certain incubation (or inhibition) period the second phase suddenly precipitates. In 5 % Ag alloy, damping (Fig.35) and hardness (Fig.36) measurements were made together with X-ray analysis. At 200^{o}C and below, low temperature aging behaviour was observed, where as at 300^{o}C a high temperature behaviour was discovered. Damping curves showed 3 stages. At 300^{o}C X-ray analysis indicated the appearance of the γ-phase (Ag_2Al) after 16 minutes; according to the hardness measurements γ-phase precipitated after about 15-20 minutes; damping measurements indicated a precipitation after 19 minutes. This initial stage was expressed by Arrhenius equation and both the X-ray and the damping measurements yielded an activation energy of 11 Kcal/mole, which probably is the formation energy of Ag_2Al nuclei.

The phase transformations, especially those accompanied by dimensional changes, can be expected to be sensitive to external stress applications in the immediate neighbourhood of the transformation temperature. The occurance of large internal friction has been observed in the α to γ transformations in ferro nickels, in the β to ζ transition in Silver-Zinc alloys, etc. Wert's (54) work can be mentioned as a good example. Polotskii and Mordyuk (68) obtained the damping curves seen in Figs.37 and 34 for Cu-Be and Cu-In alloys respectively. The peak observed in Fig.37 was due to the decomposition of the supersaturated solid solution of Be in Cu which gave rise to the γ phase. This rise in Young's modulus was also caused by the γ precipitation. The peaks observed in Fig.38 were shown by hardness measurements and the X-ray diffraction results to be caused by the precipitation of the supersaturated solid solution Cu-In.

The large volume of work published gives a forceful illustration of the potential value of the damping methods in the detection of the transformation of phases. Fig.39 shows a damping peak which is due to a martensitic type reaction in Nb-H α-solid solution. Wert et al (69) have also found a phase transformation peak due to Nb-H eutectoid (Fig.40).

Starodubov et al (70) have studied temper brittleness and blue brittleness of steels by the internal friction method. They have found that temper brittleness is caused by the increase in the binding forces of the impurity atoms to dislocations and by the increase of the concentrations of these atoms near dislocations. In carbon steels the strength decreases with increasing temperature while plasticity increases. Blue brittleness is observed at certain temperatures and is known by the formation of a blue oxide

film on the surface. This film is accompanied by the increase of strength and the decrease of plasticity and ductility. Dolzhenkov and Lotsmanova (71) observed that this behaviour is mainly due to interaction of impurity atoms with dislocations and a sudden increase in the internal friction appears at a critical strain amplitude ($\sim 5\times10^{-5}$) which marks the beginning of the amplitude dependence in internal friction.

The detection of flaws offers a special field of application for damping measurements. Any inhomogeneity may be expected to increase the damping capacity, since energy should be dissipated at the site of the flaw, either as a result of stress concentration or of solid friction. The size of the defect that can be detected depends on whether the energy dissipated at the flaw is a significant proportion of the total normal energy dissipation in the specimen. With cylindrical pieces it is possible to determine the position of a crack in the piece. A homogeneous specimen with stresses or discontinuities has an anisotropy of damping . For example, the square cross-section specimen seen in Fig.41 will exhibit different values of damping as well as different natural frequencies for two different orientations.

It was reported from AERE, UK, Harwell (98) that flaws have been detected in objects by damping measurements. The resonant frequencies were located empirically and the damping measurements were made in the vicinity of these frequencies. This work ,of course, depends a great deal on where one places the driver and pickups and on the response characteristics of transducers, electronics, and sample looked at as an integrated system. As a way of learning about some aspects of this, they have built a laser interferometer system capable of measuring surface displacements in the vicinity of transducers, as a calibration facility.

The most extensive investigation of the use of damping measurements for flaw detection is that reported by Frommer and Murray (72). They found transverse and longitudinal modes of vibration to be less suitable for this purpose than the torsional mode. These investigators devised a special system for suspending bars 2 - 2.5 m in length and 20 - 25 cm in diameter and used it in the examination of production materials such as cast ingots, forged billets, and extrusions. Their technique was used to test magnesium alloy bars 200 cm long and 19 cm in diameter at one end and tapering to a diameter of 8 cm at the other end. One bar contained a longitudinal crack in the middle region of the specimen. During the test the damping capacity was measured at the fundamental frequency and at several harmonic frequencies. Fig.42 shows the test results; the damping capacity of a sound bar is much less than that of a cracked bar. The effect of small cracks on the characteristic damping curve is very marked and in certain cases affords a convenient indication of failure by fatigue. High-strain damping is very sensitive to the presence of cracks in brass cartridge cases (73). The technique consists in exciting longitudinal resonance vibrations by producing an eddy current loop around the mouth of the case, which is situated in the radial field of a magnet. In operation, the power required to produce a stress amplitude of 10 000 psi is measured and is found to rise appreciably when the case is cracked.

4. RELATION OF FATIGUE TO THE DAMPING PHENOMENA

There is a growing tendency to attempt an explanation of fatigue processes in terms of dislocation mechanisms and, in bcc metals, particularly in terms of dislocations with point defects. Hence investigation of internal friction due to dislocation motion proves a powerful tool in the study of basic fatigue mechanisms (74). Further, fatigue itself is both produced and studied by the internal friction of sufficiently high strain amplitudes. By employing the internal friction technique in fatigue studies, it is possible to follow the conditions created by various stresslevels after a certain number of stress cycles most directly by means of changes in dislocation damping.

In order to develop high amplitude waves, a transducer is coupled to an exponential brass horn (75). In a particular form the transducer consists of a barium titanate hollow cylinder, polarized in its thickness direction, and attached to an exponential brass horn which steps up the strain by a factor of 12 (approximately given by the ratio of the diameter of the two ends of the horn) from the strain in the titanate which is limited to about 10^{-4} (Fig.43). A second tapering horn, attached to the narrow end of the first horn, is divided to enclose the sample of the test material, e.g. lead, which must have a lower Young's modulus than the material of the horn. In this manner the strain set up in the sample may be of the order of 200 - 300 times that in the titanate . To minimize any possible heating effect in the specimen and also the setting up of lateral vibrations, the system is pulsed instead of being continuously excited. The Q^{-1} of the material is deducted by measuring the Q^{-1} of the system with and without the specimen. Fig.44 illustrates measurements of fatigue strength and internal friction as a function of number of deformation cycles. The internal friction curve has three definite regions correspon-

ding to three stages of fatigue fracture (76). Obviously investigations of the fatigue by the internal friction method give much more useful information than direct investigations of the strength during cycling. Schenck et al (77) made observations on the change of damping and Young's modulus in a 0.22 %C steel (normalized condition: yield point = 31.7 Kg/mm^2, fatigue limit = 21.0 Kg/mm^2) subjected to fatigue stressing at 3100 cycles/min in a rotating bending machine. Measurements were made at various intervals; the results are summarized in Fig.45. An initial rise in damping with number of stress cycles is seen for various stress levels, changes in damping were deduced to be mainly due to dislocations. At stresses below the fatigue limit (21 Kg/mm^2), the leveling off and the decline in the curves are induced by strain aging accelerated by the temperature rise during fatiguing.

Mason (75) has developed several dislocation models for fatigue phenomena. These models include mechanisms such as impurity pinning of dislocation networks and dislocation generation by the Frank-Read mechanism, jump of dislocations over Peierls barriers, breakaway and repinning of dislocations to the impurity atoms, holding up of Frank-Read sources by cross dislocations, cutting of dislocations through the pinning dislocations, thus producing jogs, vacancies, and an uncontrolled number of Frank-Read loops. The close connection between fatigue and the rapid rise in the internal friction curve suggests that fatigue is caused by some process connected with the multiple production of Frank-Read dislocation loops. Since dislocation loops are longer near the surface and are sometimes single-ended, they require only half the stress to actuate than is necessary for double-ended loops. Therefore it appears likely that fatigue cracks are initially produced on the surface. It follows from this argument that in order to improve the fatigue properties, the operation of dislocation sources must be prevented either by locking dislocations by impurities or by increasing dislocation density, hence shortening the dislocations as by cold work or by simply decreasing the grain size of the material (78).

5. STUDY OF CREEP BY DAMPING

Zubekhin et al (79) observed a definite correlation between the creep and internal friction curves (Fig.46). These curves suggest that migrating defects are responsible for the internal friction in the process of creep and that all stages of creep can be studied from the internal friction behaviour of nickel. At 823, 873 and 923°K(curves 1', 2' and 3' of Fig.46) the internal friction increases rapidly in the first 3 - 4 min. This is evidently due to an increase in the number and length of moving dislocations before a sudden fall. In this case the dislocation density continues to rise, but there is rapid development of mutual intersection of dislocation lines; the length of dislocation segments diminishes quickly. For this reason Q^{-1} falls suddenly.

In the second stage of creep there is no change in the internal friction. At the third stage, under certain experimental conditions the moment comes when cracks appear in the metal and rapidly develop. The dissipation of energy also rises abruptly.

6. DETECTION OF MICROCRACKS BY DAMPING

Measurements of damping can give information on the origin of defects, such as the formation of quenching cracks. For example, an increase in damping was found in a steel specimen which had been quenched. The increase in damping was attributed to the formation of microcracks owing to excessive quenching temperature . Such cracks are not easily found in the structure, and the time at which they are formed is difficult to determine. Damping measurements may be used for determining hardening ranges and the effect of multiple hardening.

Intergranular corrosion increases damping . Damping measurements, therefore, constitute an excellent means of following intergranular corrosion. In many cases, the beginning of intergranular corrosion can be established after a few minutes of attack by a corrosive solution. Measurements of damping have one great advantage over other methods in that the corrosion process can be observed on a single test specimen as it is not destroyed in the test.

Now we would like to mention briefly the nondestuctive investigation of corrosion and quenching cracks which was made by the internal friction method (80). Tsobkallo (80) used two different apparata as shown in Figs.47 and 48. The one in Fig.47 is for small samples 35 mm long; because of the short length of the samples, they were clamped between longer ferromagnetic pieces. This long composite sample was suspended at two points and subjected to transverse oscillations.The amplitude of oscillations of the composite sample was measured with a microscope. This apparatus was also used later (81) by the author for measurements at high temperatures and stresses. For testing structures

and brass pipes the apparatus of Fig.48 was used. The pipes were suspended by four strings at equidistant points and radial oscillations were excited by eddy currents which were induced in the walls of the pipe. The sound waves created by the pipe are picked up by the microphone of the counter and sent to the electronic circuitry. By this method corrosion cracking in brass pipes - 80 mm in diameter and 360 mm long with a wall thickness of 1.5 mm- that were suspended above a 25 % solution of ammonia were studied. The measurements were made at 930 cps frequency at different times up to 24 hrs. The amount of cracking was measured by relative increase of the decrement. The cracked pipes were thoroughly examined and the total length of visible cracks was measured. The results of these measurements are given in Fig.49. Mima et al (82) and Mima and Yamane (83) have also investigated the relation between stress corrosion cracking and internal friction of 18-8 Austenitic stainless steel and Cu-Zn alloys. Their tests were made under a tensile stress of 80 % and 70 % yield stress in 42 wt % $MgCl_2$ and 2 vol. % NH_3 aqeous solutions respectively. As it is observed in Figs.50 and 51, the internal friction increased remarkably when the stress corrosion cracks propogated. This was due to the increase in the density of dislocations corresponding to a small amount of plastic deformation around cracks.

Considerable stresses resulting from quenching also induce visible cracks. Submicroscopic cracks occuring as the result of quenching also have a considerable effect on the strength of the material. Thus it is very tempting to apply the measurements of the decrement of oscillations to the study of the effect of submicroscopic cracks which cannot be detected.

Förster (17, 84) used the apparatus illustrated in Figs.18 and 52 for investigation of "material microstructure effects" such as the external and intercrystalline corrosion depth and the quantitative observation of the formation of fatigue fractures by damping measurements. Fig.52 is the same as Fig.17 , the only difference being the additional gate provided between the amplifier and the counter which passes the oscillations of amplitude A and A/e . The number read on the counter is the reciprocal of the damping (Eqn. 22) .

Förster (17) obtained the damping curves shown in Fig.53 for 0.9 %C steels quenched from 900°C and 1100°C. The steel quenched from 900°C shows a slow damping decrease due to the equalization of internal stresses, but when quenched from 1100°C , the steel shows a damping, which due to the formation of microcracks with time, increases to 300 % of the value which was measured immediately after quenching. Förster and Schneider (85) had also obtained an enormous increase of damping capacity due to inter-crystalline corrosion of very shallow depth. The grain boundary decay appearing in intercrystalline corrosion corresponds exactly to the effect of microcracks. The results shown in Fig.54 belong to Al-Mg (11 %Mg) alloy after it was quenched from 450°C and afterwards annealed at various temperatures. Annealing increases corrosion sensitivity of the alloy. According to the results of Tsobkallo's (80) investigations on Cr-Ni steels and on 1.3 %C steel as seen in Fig.55 the number of cracks apparently increases with the rate of cooling during quenching. Two series of Cr-Ni steelsamples were maintained at 850°C for 15 min and then quenched in water and oil. To exclude the effect of structural differences on the decrement, all the samples, regardless of their treatment, were quenched in oil again. Curves 1 and2 in Fig.55 indicate clearly that the internal friction is much higher for samples quenched in water. An annealing treatment carried out under the same conditions at 700°C did not eliminate the differences between the samples but decreased the internal friction. The main cause of the difference is the occurance of submicroscopic cracks in samples quenched in water. Further experiments with quenched steel containing 1.3 %C directly confirmed the relationship between the increase in the damping and the presence of cracks observed either directly with the microscope or put in evidence by the graphitization method.

Damping increases by a factor of threee or four as the result of stress corrosion cracking of brass or as the result of rapid quenching of steel.

Tsobkallo (80) claimed that this method could be used to detect defects in parts or complete structures employing a defectophone together with other methods of defectoscopy (ultasonic , X-ray , magnetic). The dfectophone would be very sensitive and would make it possible to detect defects within a body. Hence it would be possible to conduct a qualitative study of large structures (plates and pipes) and massive parts of machinery (cast turbine blades,etc.). Later in 1967 Titov and Devichenskii (86) tested aero-engine blades using this method. They measured the change in internal friction as a function of the service life using a semi-automatic apparatus (87) designed specially for this purpose.

In this apparatus , as shown in Fig.56, the turbine blade is clamped hydraulically,

and bending vibrations are induced in the blade by deflecting it by a lever and then releasing it suddenly by dropping a freely falling disk on the lever.

IV. CONCLUSION

The result of our investigations shows that "damping" or "internal friction" measurements can be employed for the study and detection of macroscopic defects as well as microscopic.

The last decade has witnessed in the progress of nondestructive testing techniques that a gradual transformation has occured from macroscopic properties of materials. This extended the capabilities of nondestructive testing techniques to their ultimate limits, i.e. to the determination of the physical and mechanical material properties such as the dislocation densities, the distribution and concentration of point defects, the interaction energies between point defects and dislocations , etc. Thus it is quite obvious that in the near future the damping properties of materials will carry much greater weight in the nondestuctive testing technology .

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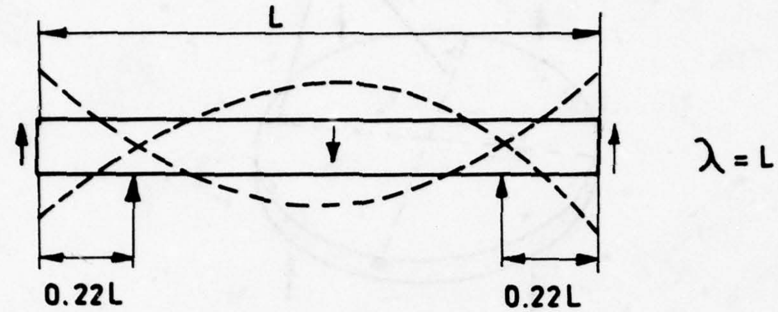


Fig.1. Flexural vibrations, fundamental mode.

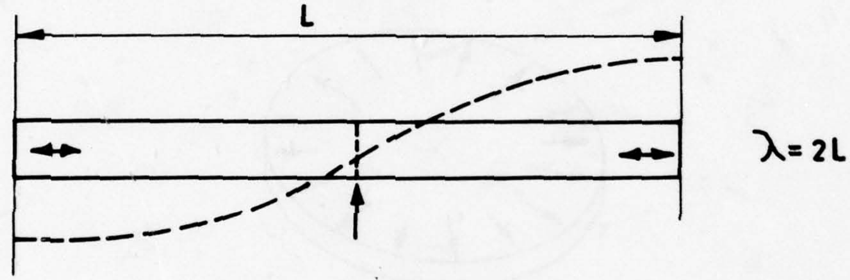


Fig.2. Longitudinal vibrations, fundamental mode.

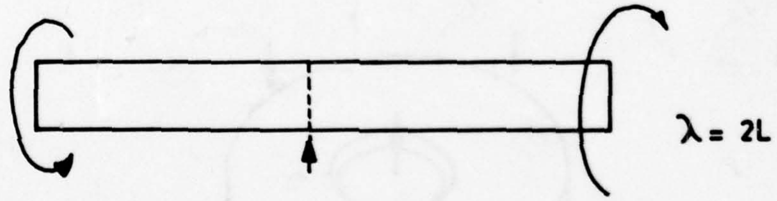


Fig.3. Torsional vibrations, fundamental mode.

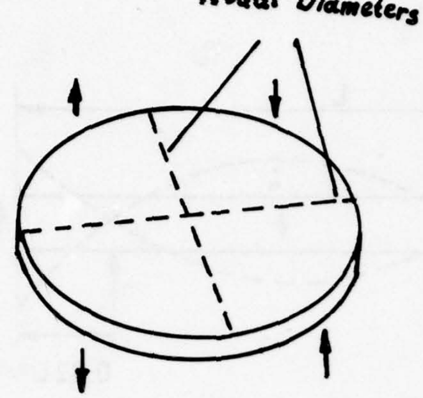


Fig.4. Flexural vibration of a circular disc.

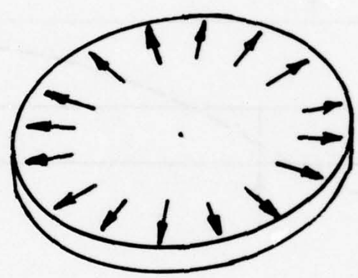


Fig.5. Radial vibration of a circular disc.

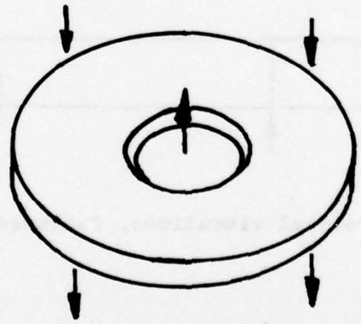


Fig.6. Flexural vibration of a circular plate with an axial hole.

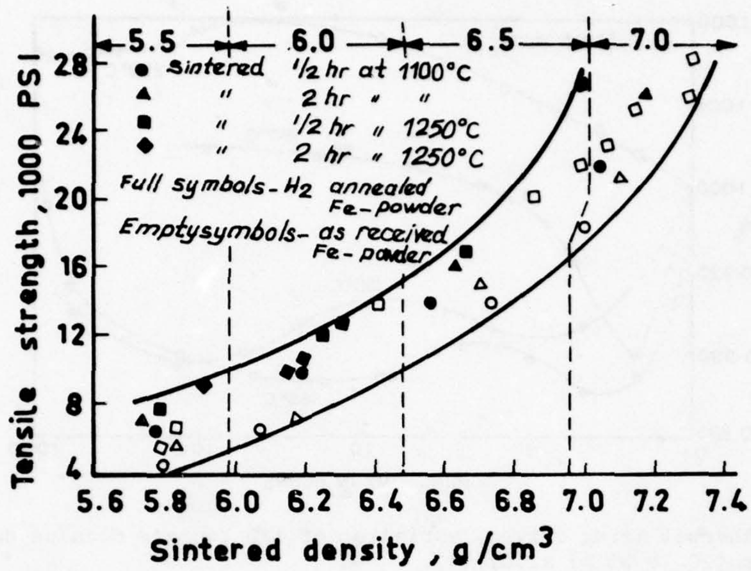


Fig.7. Dependence of tensile strength on sintered density (94).

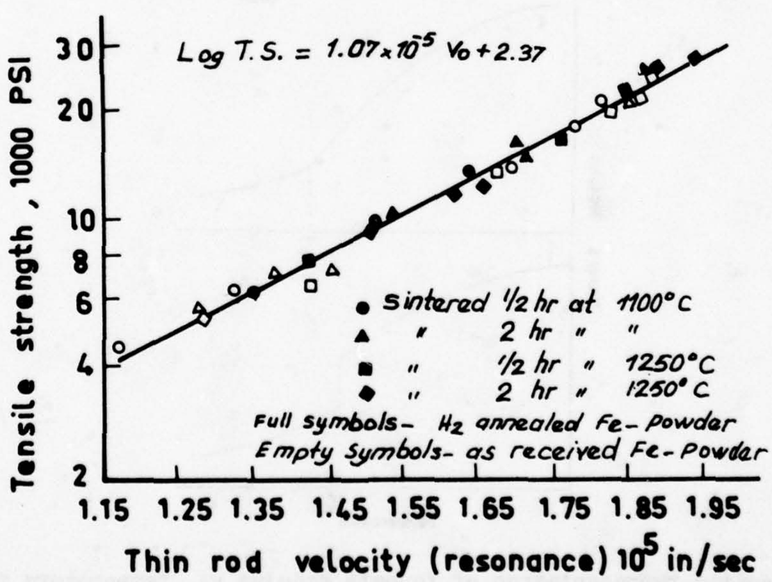


Fig.8. Dependence of tensile strength on thin-rod velocity for iron (94).

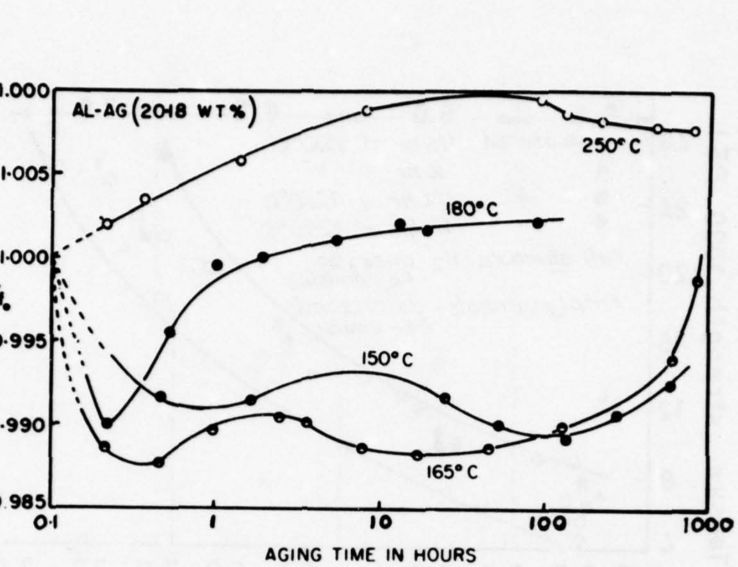


Fig. 9. Isothermal aging curves, variation of the Young's modulus during aging of Aluminum-Silver (20.18 wt %) alloy (8).

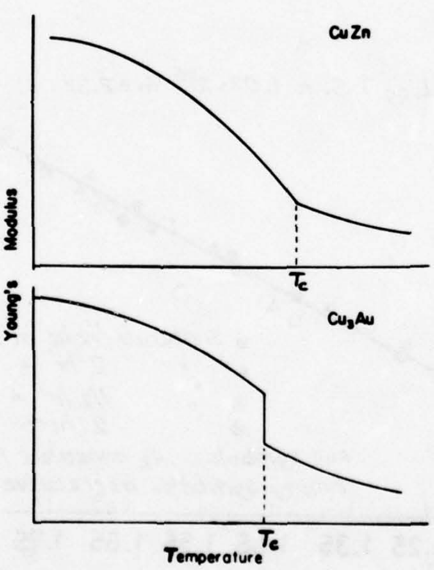


Fig. 10. Schematic representation of Young's modulus vs. temperature for the ordering systems CuZn and Cu_3Au . T_c is the so called Curie or "Ordering" temperature.

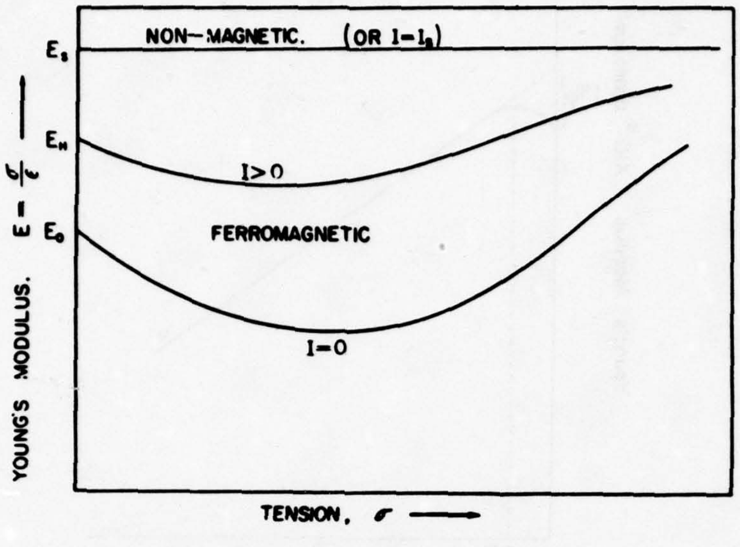


Fig.11. The dependence of Young's modulus of a ferromagnetic material on magnetization and stress amplitude (9).

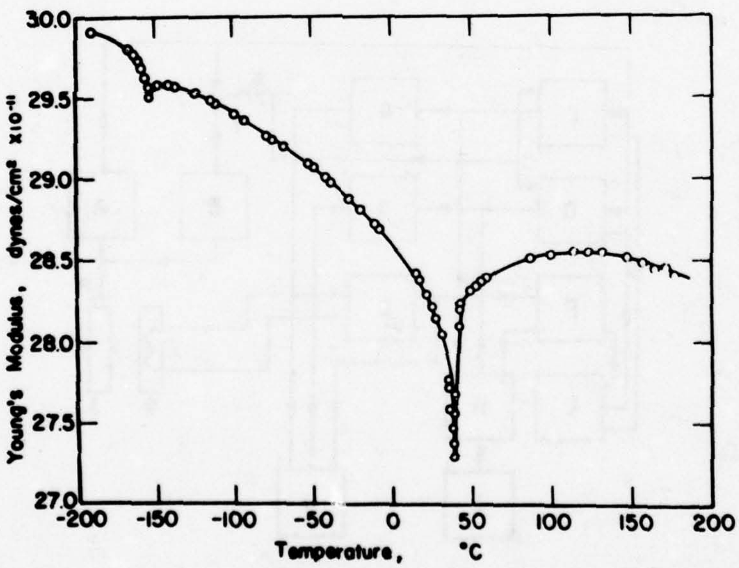


Fig.12. Young's modulus vs. temperature for electrolytic Cr (10).

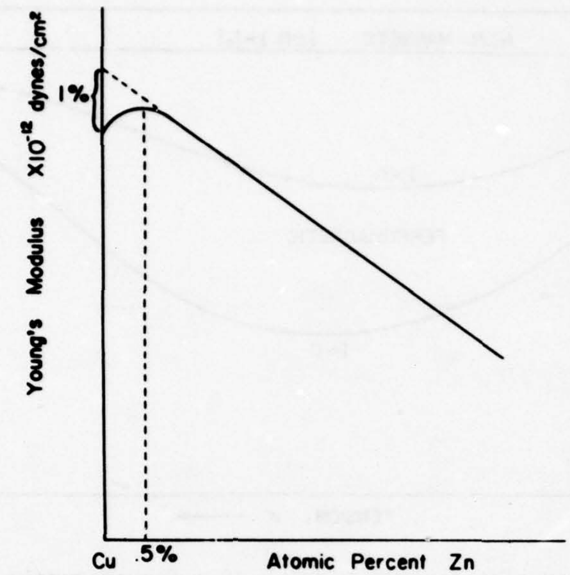


Fig.13. Schematic Illustration of Young's modulus vs. composition for dilute Cu-Zn alloys (11).

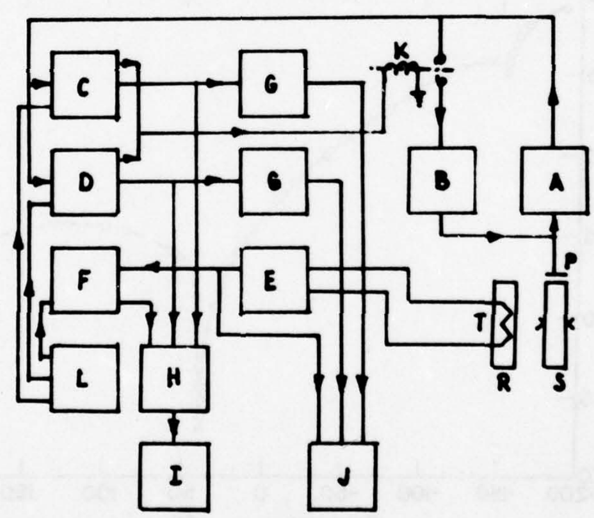


Fig.14. Automated system for electrostatic excitation and detection of longitudinal vibrations. A. Detection device; B. excitation amplifier; C. decrementmeter; D. periodmeter; E. supply and amplifier of the platinum resistance thermometer; F. analogue-to-digital converter; G. digital-to-analogue converter; H. gates; I. counter and tape punch; J. multichannel recorder; K. excitation relay; L. control unit; P. pick-up electrode; R. temperature reference sample; S. sample under test (14).

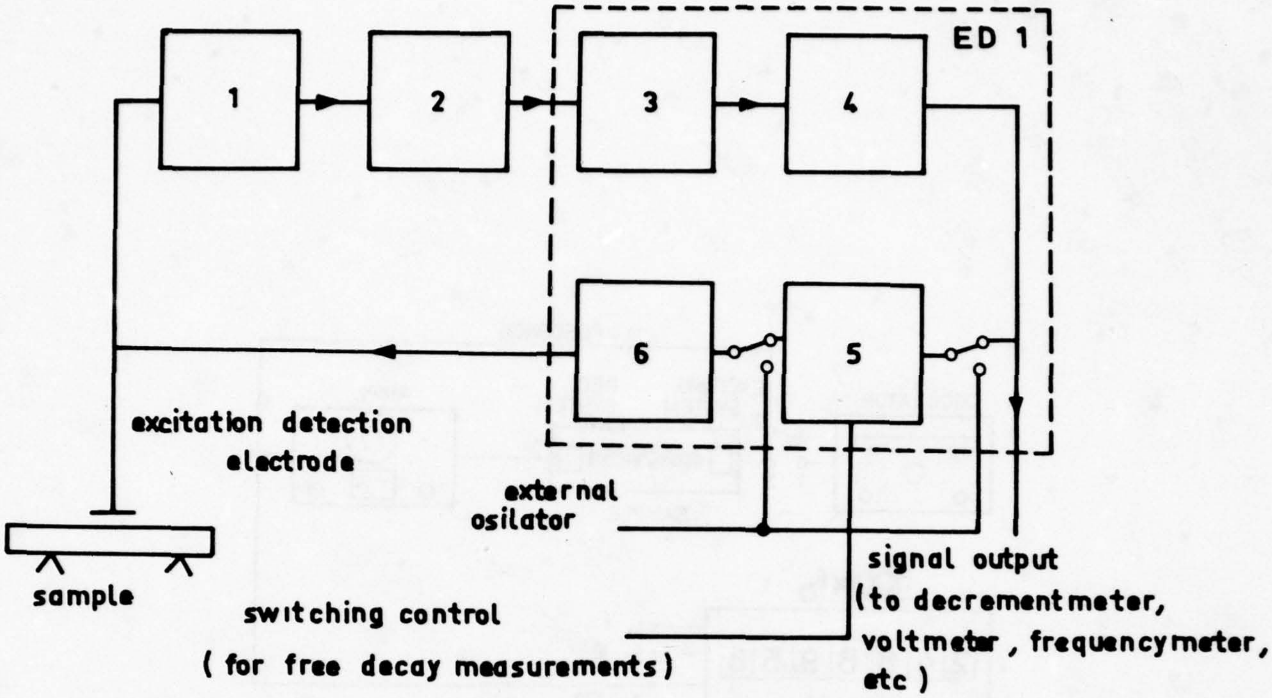


Fig.15. Automatic arrangement for electrostatic drive and detection of flexural vibrations. 1. Oscillator (VHF frequency modulated); 2. VHF tuner (e.g. Rhode and Schwarz Frequency Deviation Meter); 3. Variable gain preamplifier and phase shifter; 4. Automatic tuned amplifier; 5. Automatic gain control and electronic switch; 6. Excitation amplifier (15).

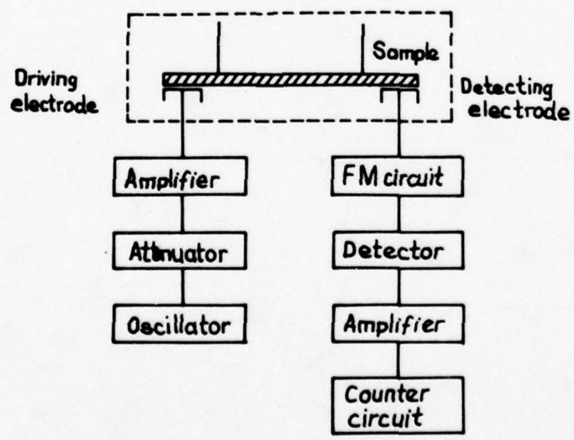


Fig.16. Block diagram of the apparatus used by Hasiguti et al (16) for transverse vibration method.

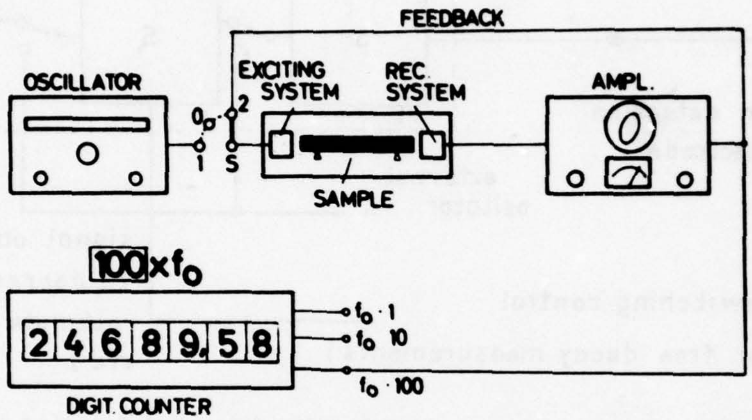
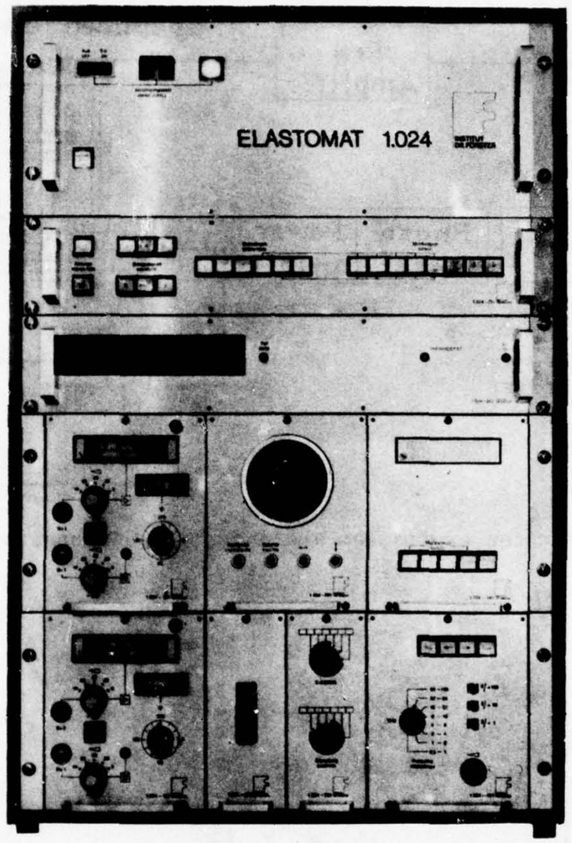
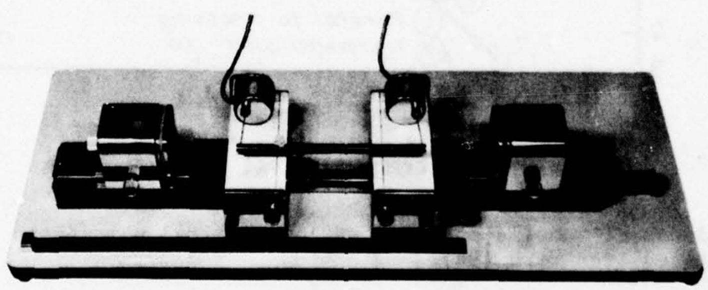


Fig.17. Block diagram of Elastomat (17).



(a)



(b)

Fig.18. a. Elastomat 1024; b. Specimenholder (18).

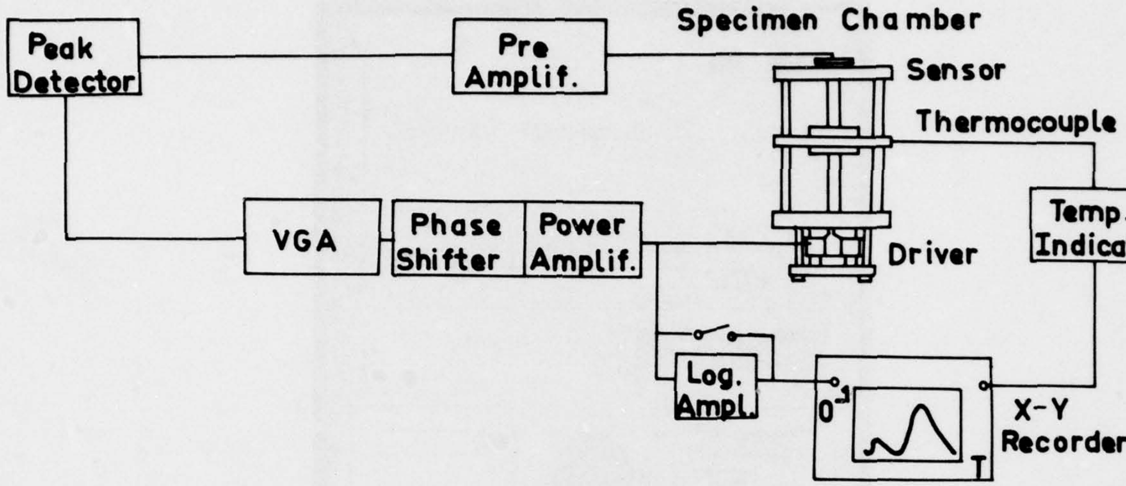


Fig.19. Automatic system for excitation and detection of longitudinal vibrations (19).

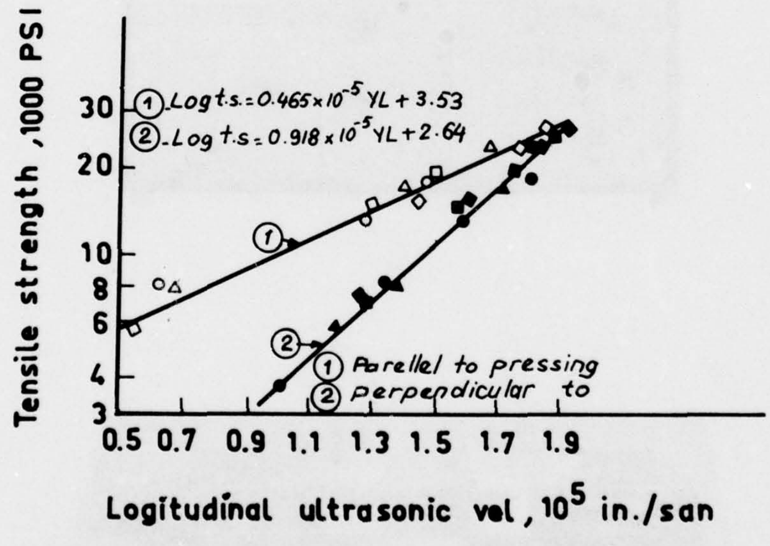
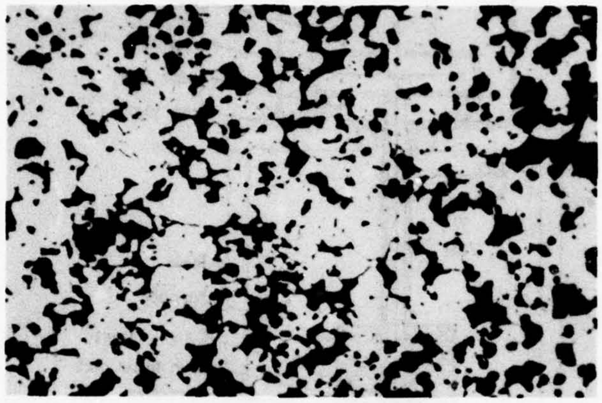
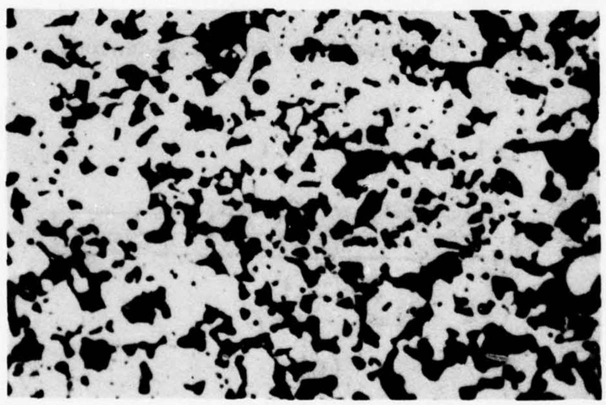


Fig.20. Dependence of tensile strength on longitudinal ultrasonic velocity for two directions in sintered iron bars (94).



(a)



(b)

Fig.21. a. Microstructures of a 316 stainless steel green compact pressed at 50 tsi parallel to pressing direction, b. Perpendicular to pressing direction (X100) (95).

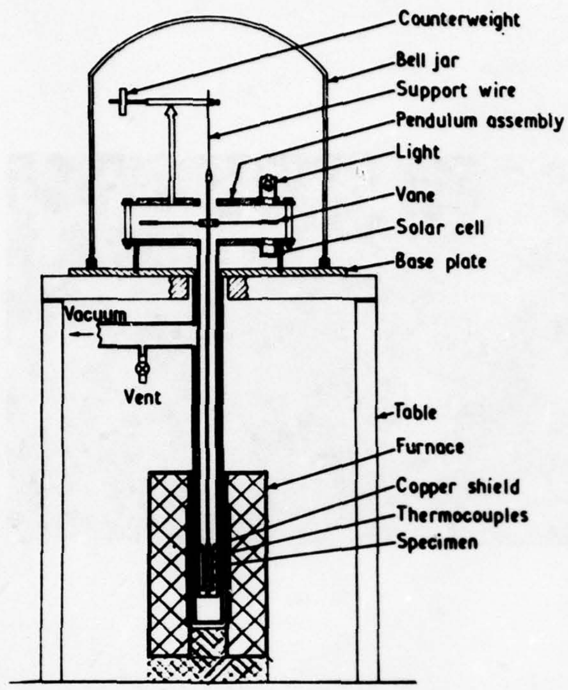


Fig.22. The inverted torsion pendulum.

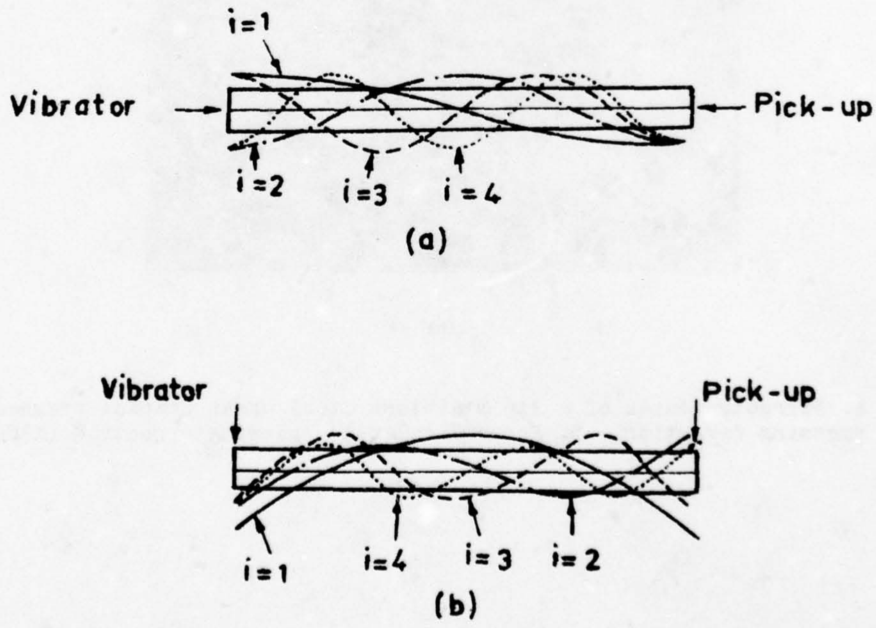


Fig.23. Vibrational displacements for various modes of vibration : a. Longitudinal and torsional mode, b. Flexural mode.

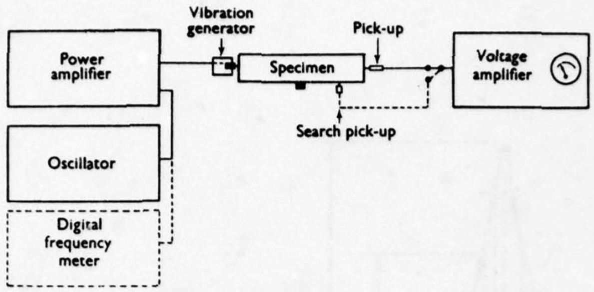


Fig. 24. Testing of a concrete beam in longitudinal mode of vibrations.

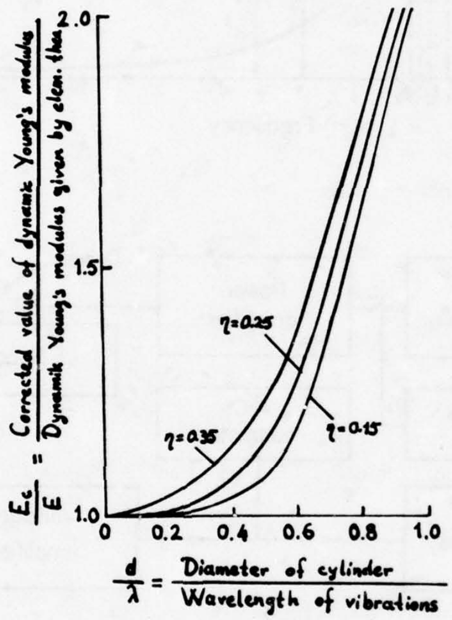


Fig. 25. Correction factor for Eq. (15), η =Poisson's ratio.

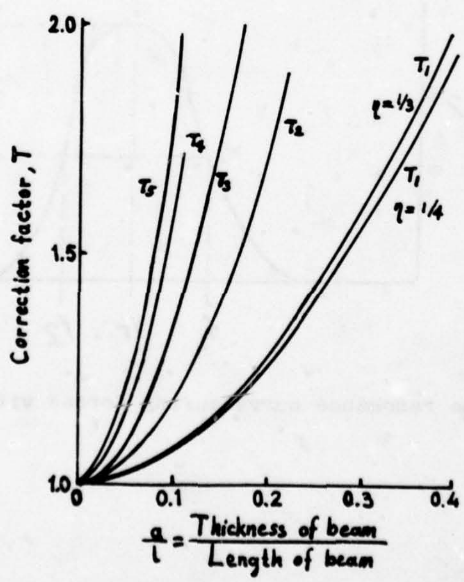
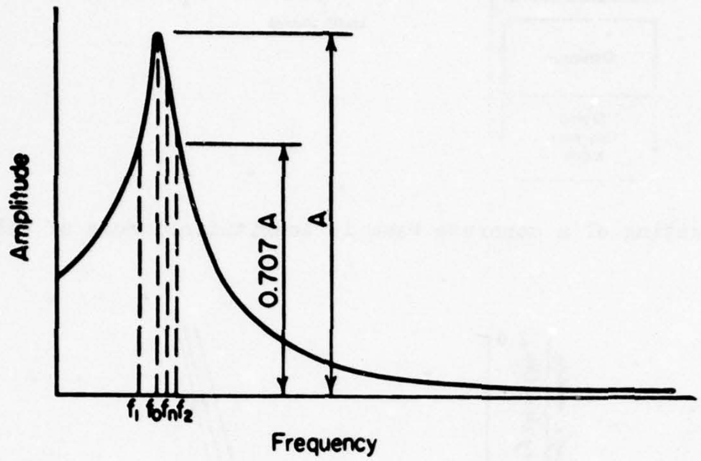


Fig. 26. Correction factor for Eq. (17).



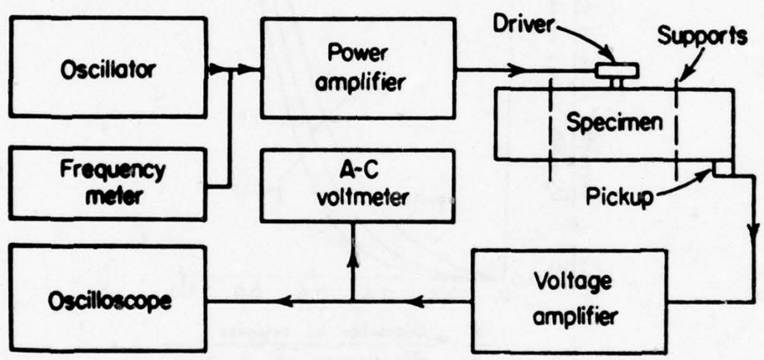


Fig. 27. Apparatus for measuring compressive strength of concrete (40).

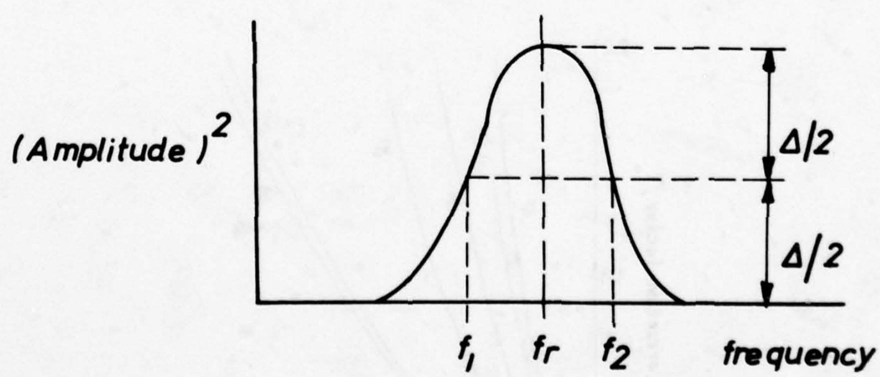


Fig. 28. The resonance curve during forced vibrations.

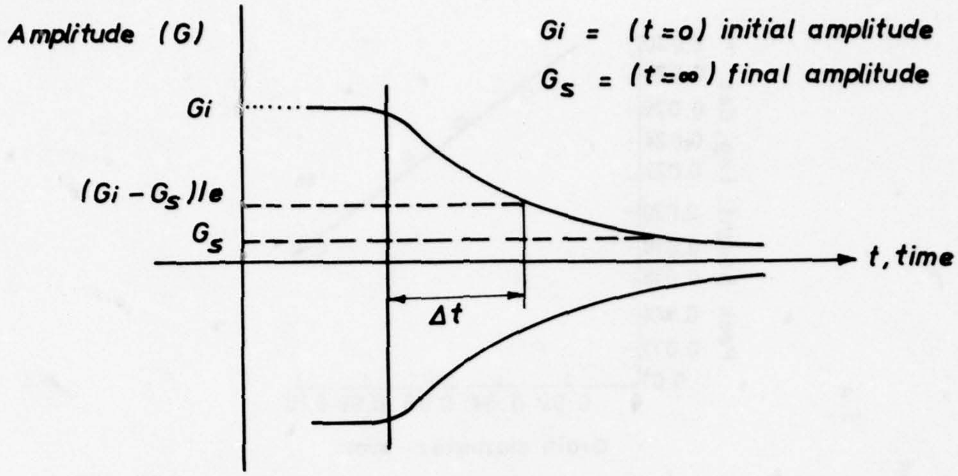


Fig. 29. The amplitude decay (damping) curve of free vibrations.

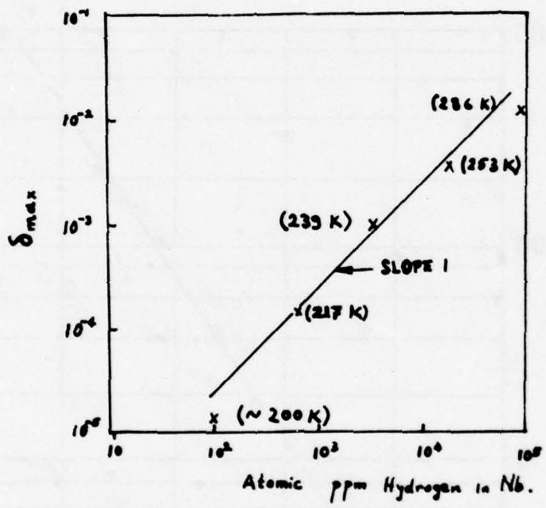


Fig. 30. The height of the internal friction peak in Nb as function of the Hydrogen concentration (61).

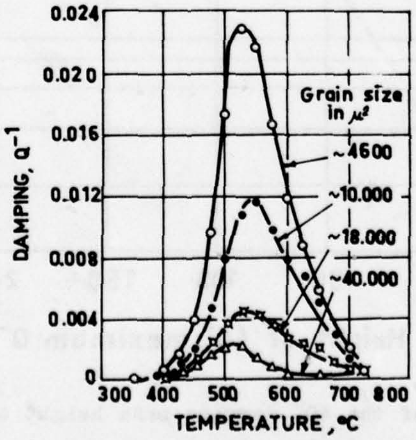


Fig. 31. Effect of grain size on Q^{-1} in Zirconium (63).

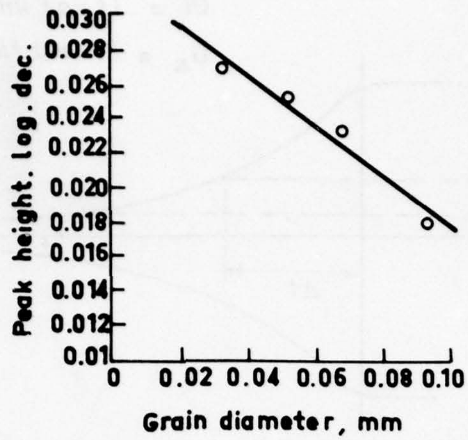


Fig.32. Variation of the grain-boundary damping peak height with grain size in iron (64).

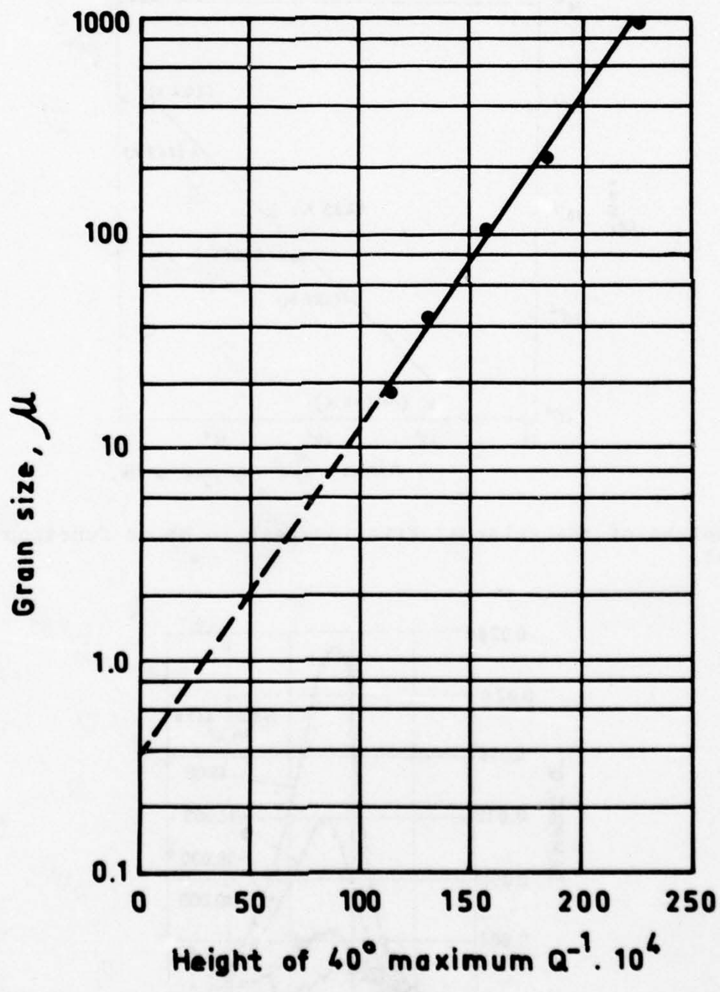


Fig.33. The dependence of the 40° damping peak height of Fe-0.04 wt %C alloy on the grain size (66).

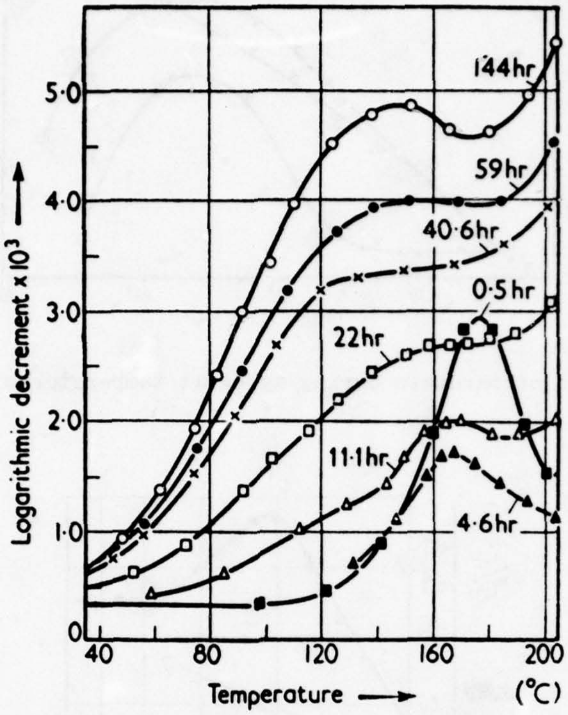


Fig.34. Changes observed in the Θ'-damping peak in an Al-Cu 4 wt % alloy with aging time and temperature (62).

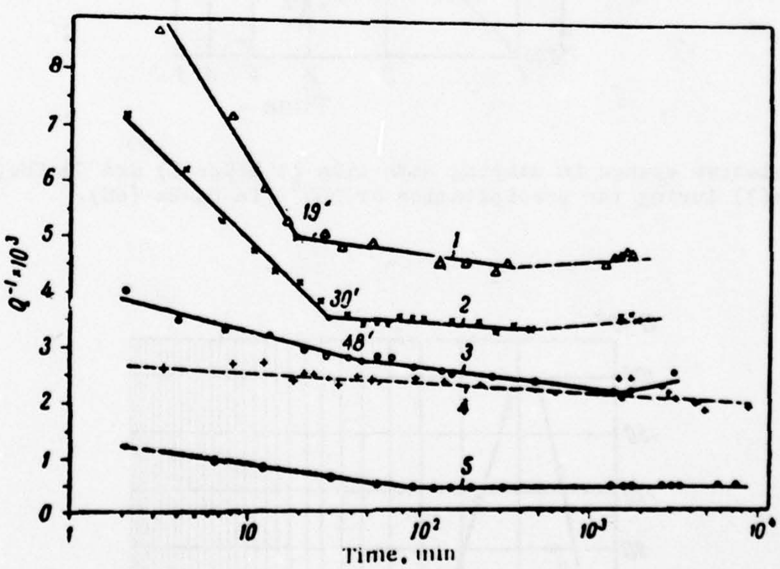


Fig.35. Variation of hardness during aging at temperatures: 1. 300°C, 2. 275°C, 3. 250°C, 4. 225°C, 5. 100°C, (62).

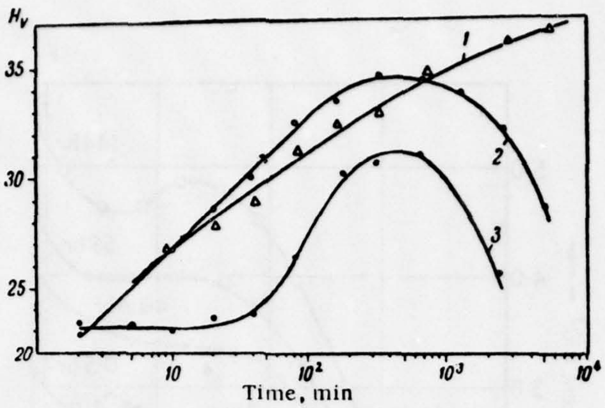


Fig.36. Variation of hardness during aging at temperatures:1. 200°C, 2. 250°C, 3. 300°C, (67).

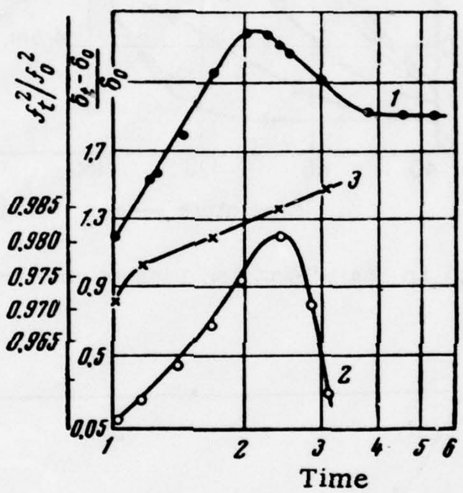


Fig.37. Relative change in damping with time at 1 KHz(1) and 21 KHz(2), and in the Young's modulus(3) during the precipitation at 300°C in Cu-Be (68).

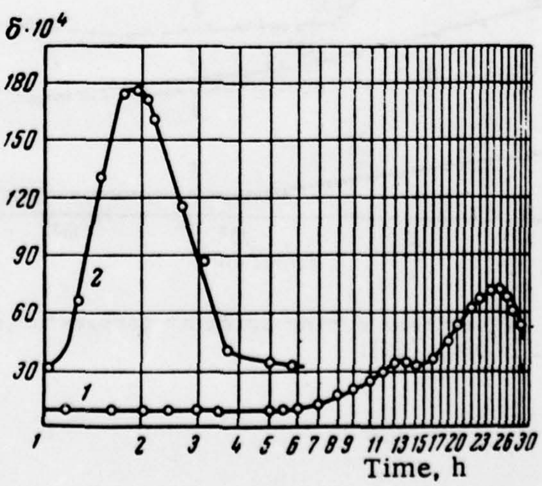
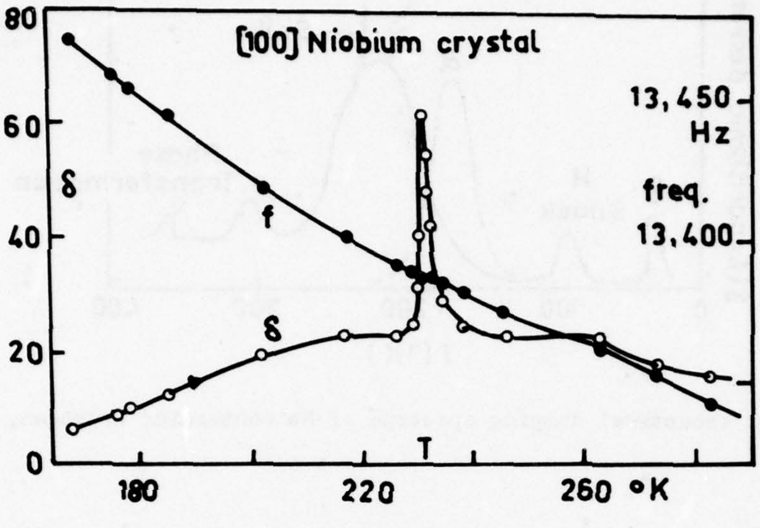
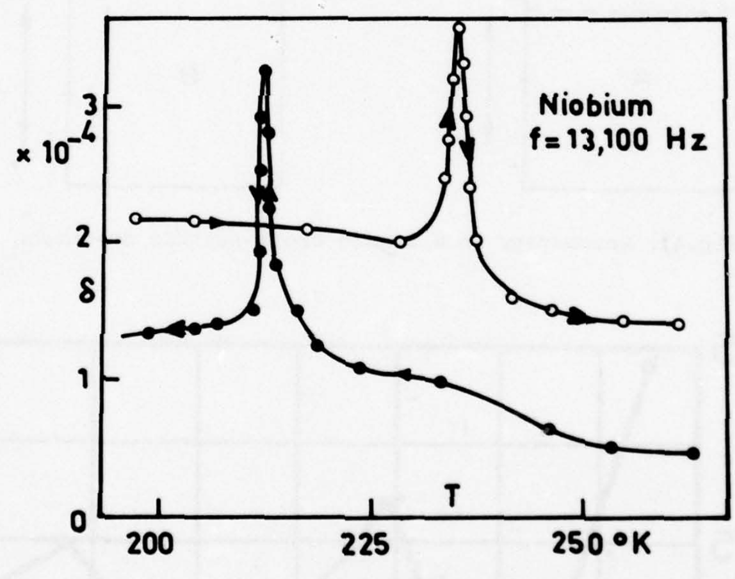


Fig.38. Change in the damping in the Cu-In alloy at 1.5 KHz at 245°C(1) and 420°C(2), (68) .



(a)



(b)

Fig.39. a. Damping spike in Nb associated with phase transformations, b. Hysteresis of the damping spike (54).

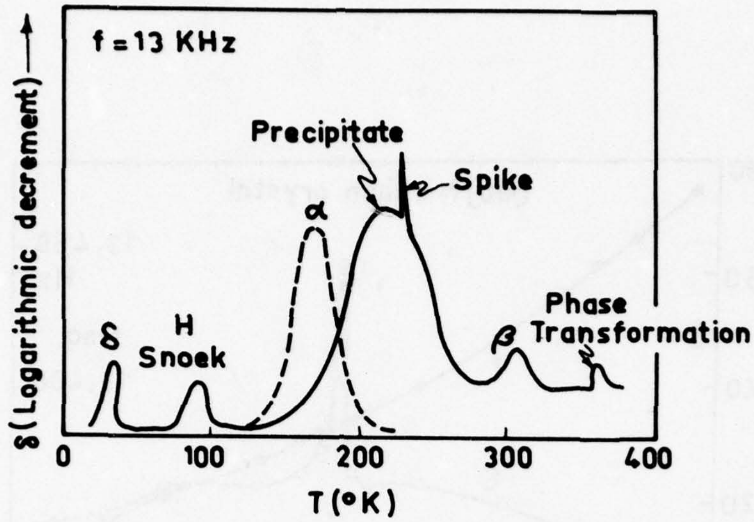


Fig.40. Acoustical damping spectrum of Nb containing Hydrogen, (69).

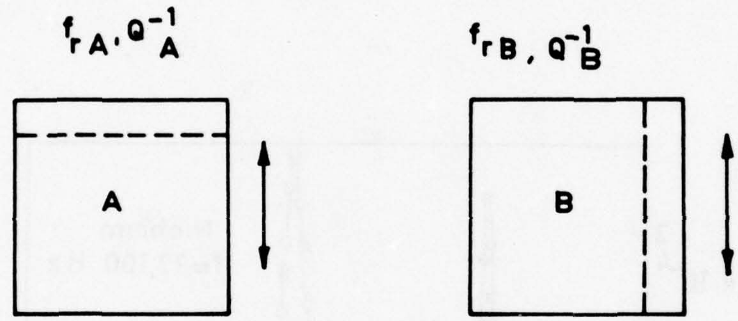


Fig.41. Anisotropy in a square cross-section specimen.

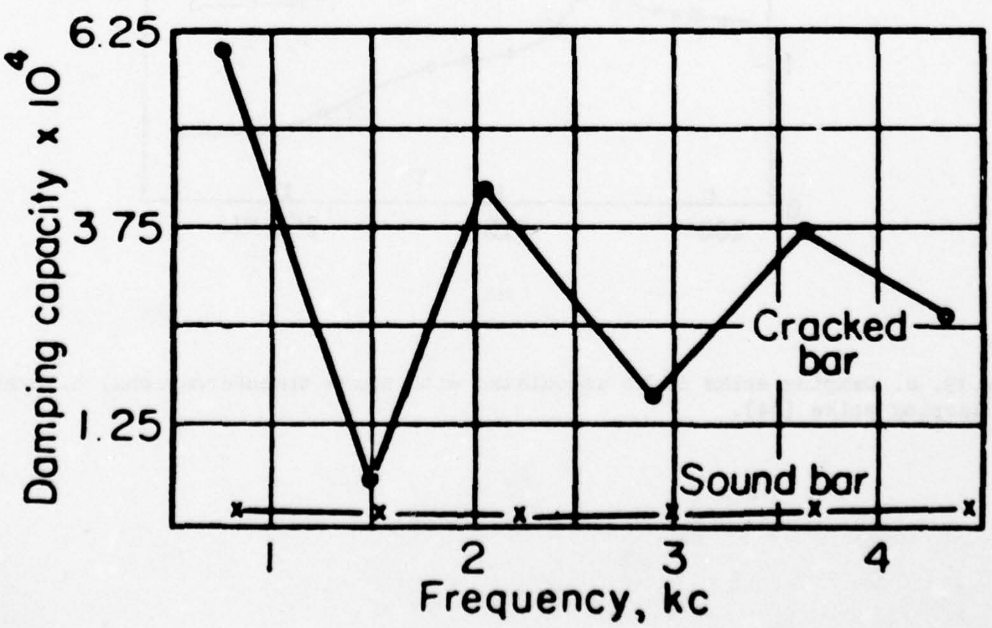
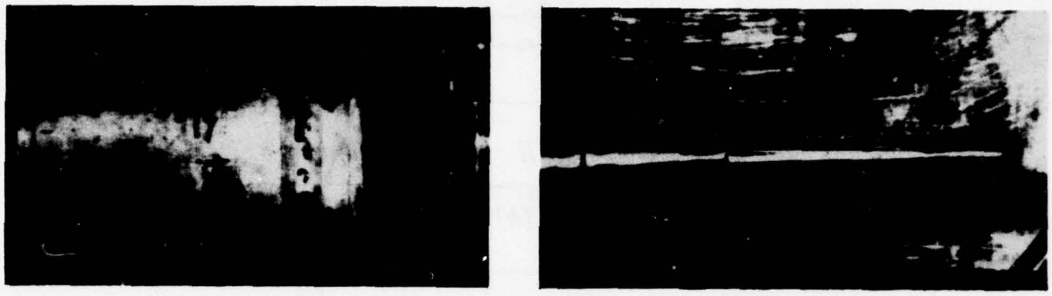
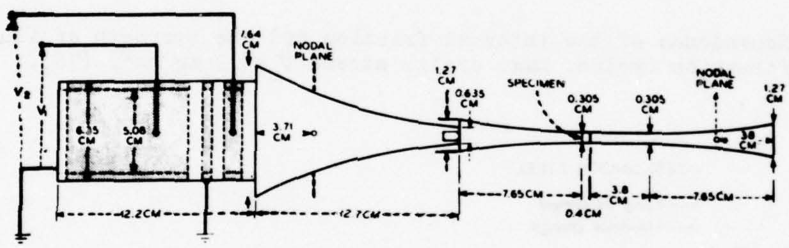


Fig.42. Damping of cracked bar.



(a)



(b)

Fig.43. a. Barium titanate driver and exponential metal horns for measuring internal friction and elastic modulus. b. A third horn has been added to the apparatus in (a) so that weights can be attached at second nodal plane,(75).

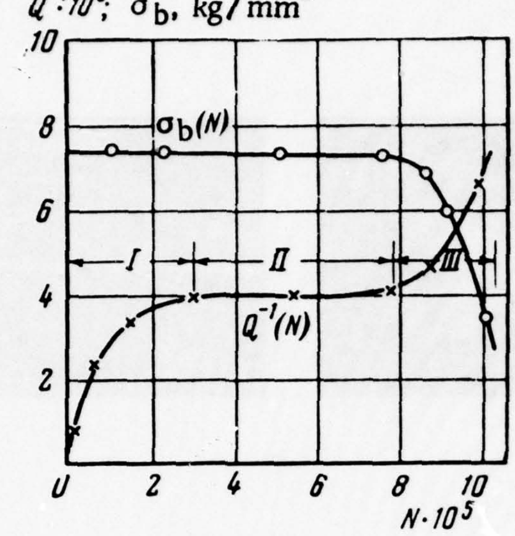


Fig.44. Dependence of the internal friction and the stre[illegible]h of Aluminum on the number of deformation cycles. Max. cyclic stress σ_m=5.3 Kg/m[illegible], (76).

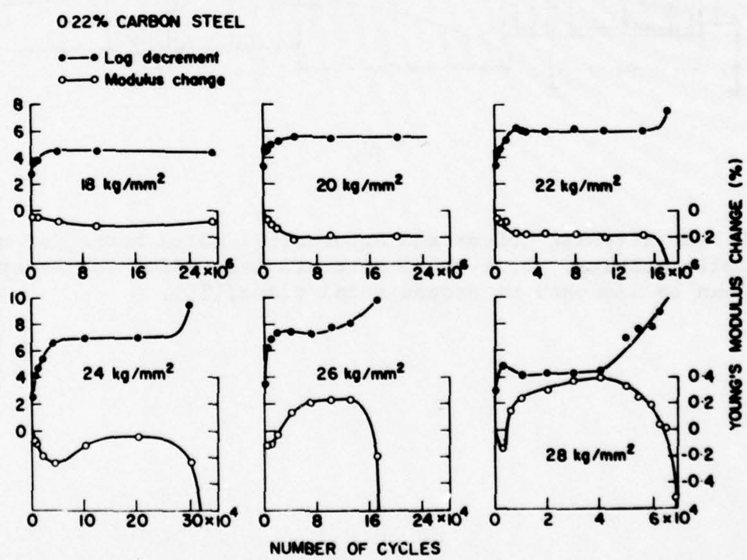


Fig.45. Variation of damping and modulus defect in 0.22 %C steel with number of cycles at cyclic stress levels below and above fatigue limit 21.0 Kg/mm^2. Measurements are made at KHz frequency range (77).

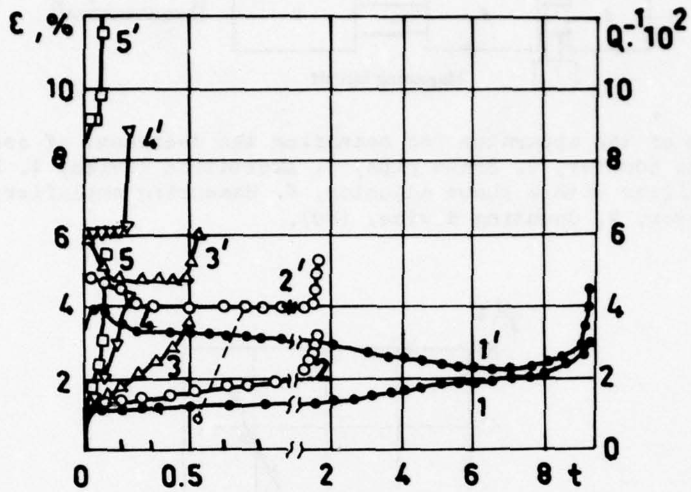


Fig.46. Internal friction behaviour of Ni in the presence of creep: 1,2,3,4,5-creep curves at 823, 873, 923, 973 and 1023°K ; 1',2',3',4',5'-internal friction curves,(79).

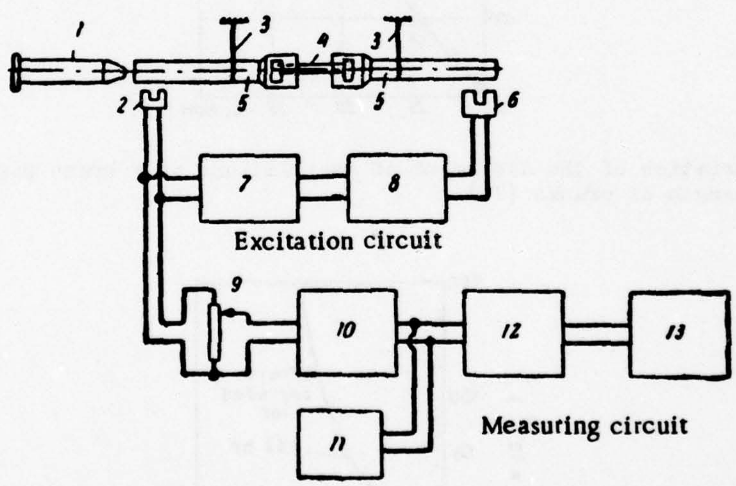


Fig.47. Diagram of the circuit for measuring the decrement of oscillations of small samples. 1. Microscope, 2. Counter, 3. Hangers, 4. Sample, 5. Extenders, 6. Excitation device, 7. Preliminary amplifier with phase adjusters, 8. Power amplifier, 9. Potentiometer, 10. Measuring amplifier, 11. Electronic voltmeter, 12. Selector, 13. Counting device, (80).

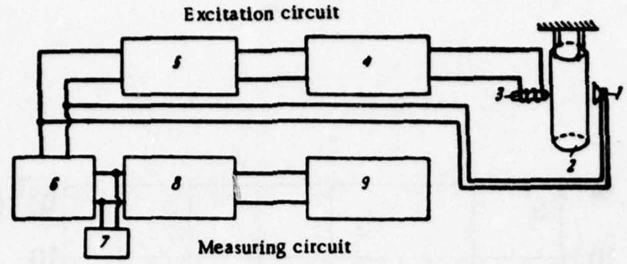


Fig.48. Diagram of the apparatus for measuring the decrement of oscillations of brass pipes. 1. Microphone counter, 2. Brass pipe, 3. Excitation device, 4. Power amplifier, 5. Preliminary amplifier with a phase adjuster, 6. Measuring amplifier, 7. Electronic voltmeter, 8. Selector, 9. Counting device, (80).

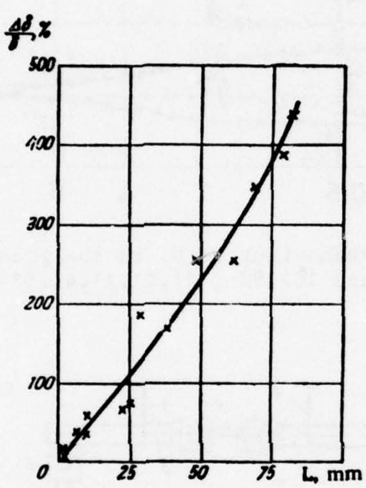


Fig.49. Variation of the decrement of oscillations of a brass pipe as a function of the total length of cracks (74).

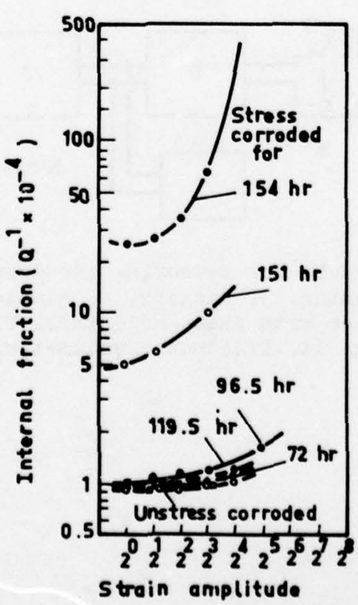


Fig.50. Strain amplitude dependence of internal friction of a Cu-Zn 35.11 wt.% sample (83).

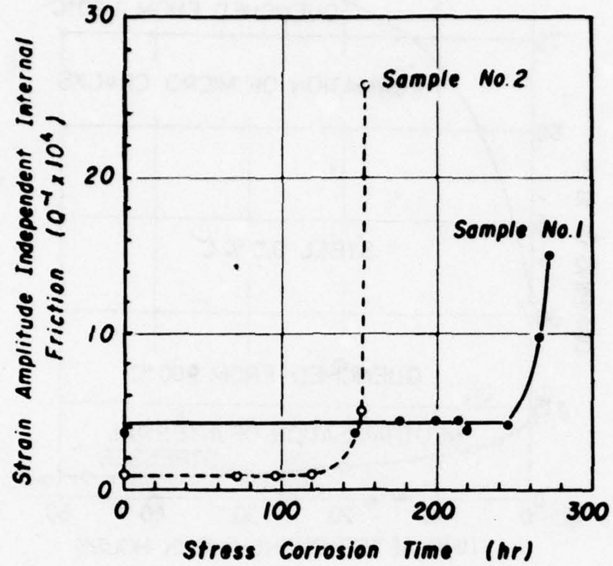


Fig.51. Changes in strain amplitude-independent internal friction with stress corrosion time, Sample No.1. Cu-Zn 30.07 wt % , Sample No.2. Cu-Zn 35.11 wt % , (83).

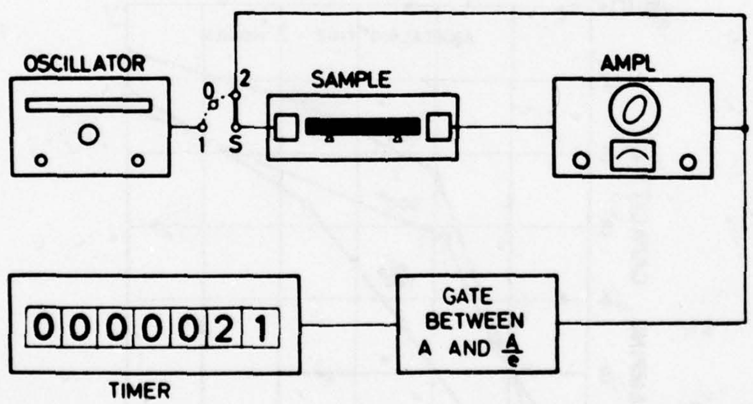


Fig.52. Block diagram of Elastomat arranged for automatic determination of damping capacity , (17).

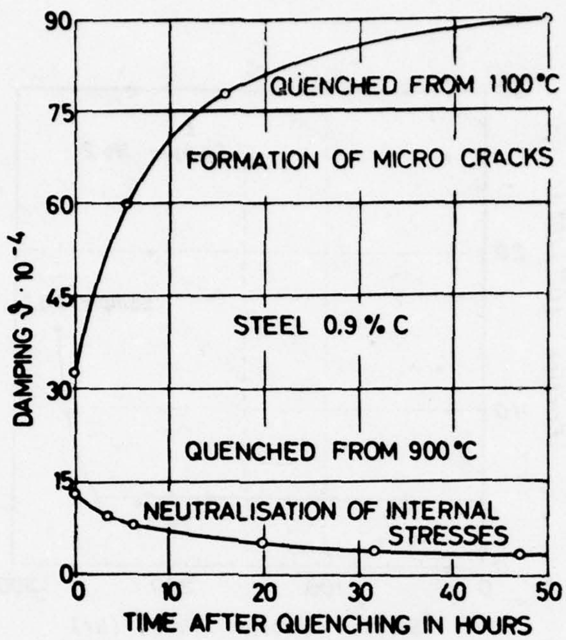


Fig.53. Variation of damping with time after quenching ,(17).

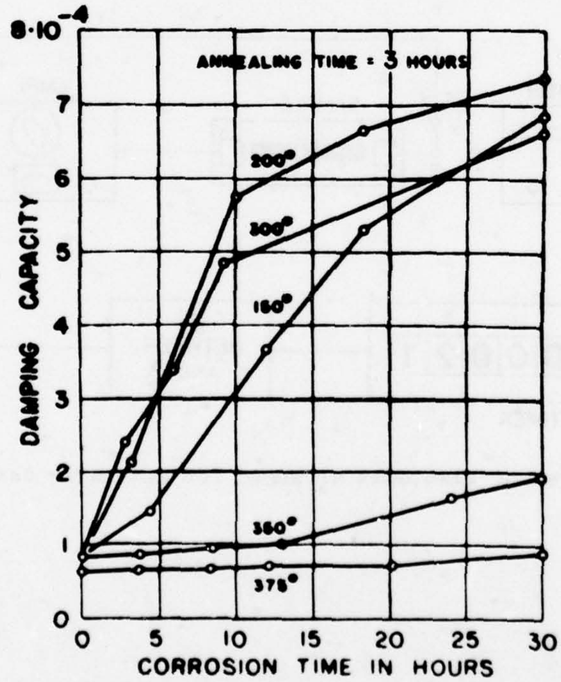


Fig.54. Variation of damping with corrosion time after annealing at various temperatures (17).

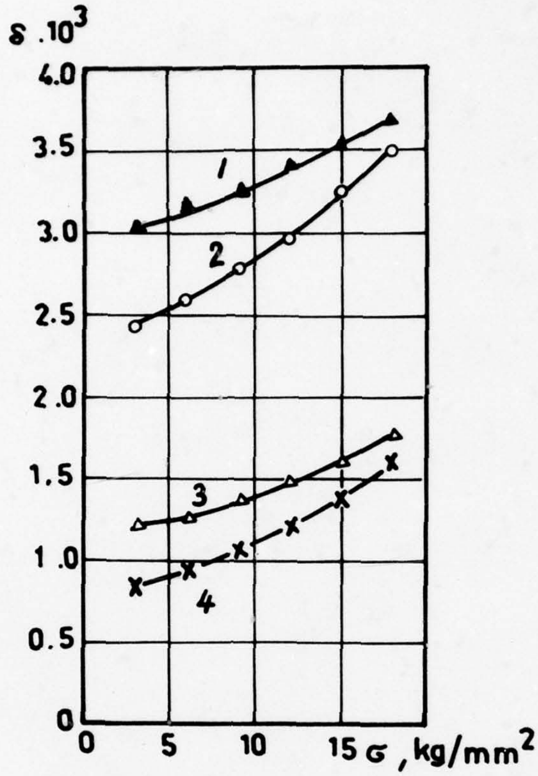


Fig.55. Variation of the decrement of oscillations with the amplitude in the case of Cr-Ni steel subjected to different heat treatments. 1. Quenched once in water and twice in oil, 2. Quenched once in water and twice in oil and annealed at 700°C for 1 hr, 3. Quenched twice in oil, 4. Quenched twice in oil and annealed at 700°C for 1 hr.,(80).

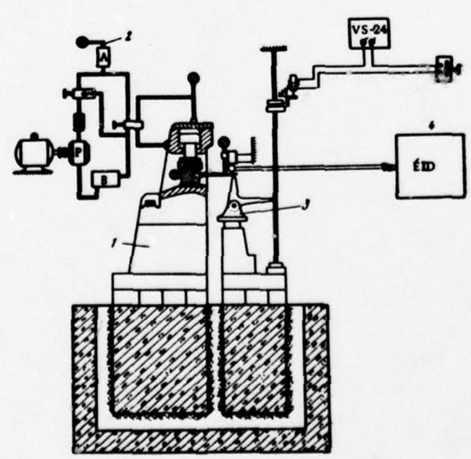


Fig.56. Schematic diagram of the apparatus used to measure the damping of vibrations in turbine blades. 1. Hydraulic press, 2. Hydraulic supply system, 3. Device for exciting vibrations, 4. Electronic apparatus for measuring the damping decrement; P- Pump, A- Hydraulic accumulator, B- Booster , (87) .

NDI METHODS ON FULL-SCALE FATIGUE TESTS AND THEIR SERVICE USAGE

by

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SUMMARY

The success and the effectiveness of NDI at a fatigue critical area during service usage depends much on the exact knowledge of the location within the structure and the crack propagation behaviour. A full scale fatigue test provides a valuable basis to determine the fatigue critical areas, to evaluate the most suitable NDI method and to fix the initiation and interval of NDI. Nevertheless all cracks and failures found in the full scale fatigue test must be checked carefully with respect to their applicability to service usage.

An additional cost effectiveness consideration gives the information, whether it is advantageous to inspect at certain intervals or to exchange the part under consideration.

1. INTRODUCTION

Within the aircraft maintenance concept necessary in order to maintain flight safety and operational readiness, inspections on the airframe due to fatigue make up a substantial part of the total effort.

Basically it is necessary to inspect:
- on the critical locations
- with the most effective methods
- after the correct number of flight hours.

As a result of these inspections, different measures must be taken:
- if no damage is indicated, the NDI is to be performed again after one inspection interval or
- if a damage is found a further observation, repair, exchange, or scrap has to be performed.

In most cases inspections and the associated measures cause considerably high costs because of the extensive amount of manhours involved, and in general, these costs are showing a tendency to increase. Therefore considerations for reducing the inspection effort while maintaining or increasing the flight safety and the operational readiness must include:

- the exact knowledge of fatigue critical locations and their crack propagation behaviour which are gained through full scale fatigue tests,

- the most effective NDI methods with respect to probability of crack detection and their costs, which can be developed within a full scale fatigue test,

- the determination of beginning and intervals of NDI within an individual aircraft tracking program during service usage.

In this chapter an outline is given for the principal procedures to select the most effective NDI methods and intervals for service usage based on a full scale fatigue test including the problems of fatigue damages undetected by NDI during full scale fatigue testing.

The term "NDI" used in this chapter includes the application of a non-destructive inspection to a definite fatigue critical location within a structure, the term "NDI method" is referred to the non-destructive technique used, the term "NDI procedure" contains the complete non-destructive evaluation (NDE).

2. GENERAL PHILOSOPHY

In FIG 1 the basic procedure for the development of NDI procedures on airframe structures during service usage is shown in correlation to the full scale fatigue test and the cost effectiveness considerations.

These non-destructive inspections shall minimize the probability of failures due to fatigue cracks in airframe structures and maintain operational readiness during the usage of the aircraft. A basis for development and testing of NDI procedures is a full scale fatigue test whose objectives are:

- proving the assumptions of the aircraft concept,
- identification of fatigue critical areas which are not identified by previous theoretical fatigue analyses or fatigue component tests,
- definition of crack propagation behaviour. [1, 17].

Out of previous investigations which comprise theoretical fatigue analysis, component tests and static tests, first assumptions for fatigue critical areas can be made. The corresponding NDI methods are assembled in a NDI survey.

With the test results for the fatigue critical locations the allowable damage indices for the initiation and the intervals of NDI can be calculated.

For cost effectiveness considerations a comparative calculation is carried out. The costs of replacing a damaged part with a new one at the moment of first inspection while disregarding the NDI procedures developed during full scale fatigue testing must be weighed against NDI at defined intervals after the first inspection.

An individual aircraft tracking program provides the basis for computation of the damage indices accumulated by each aircraft, indicating the initiation and interval of NDI by comparing the allowable damage index out of the full scale fatigue test with the individually accumulated damage indices.

The result of the NDI on a fatigue critical location during service usage must be correlated with corresponding damage occured during full scale fatigue test in order to recalculate, if necessary, the allowable damage index for the initiation and interval of NDI.

With the procedure described above, it is assured that all fatigue critical locations found in the full scale fatigue test using the most effective NDI methods are inspected at an individually adapted number of flight hours.

3. NDI DURING FULL SCALE FATIGE TEST

In order to fulfill the objectives of the full scale fatigue test and thus provide a basis for NDI procedures, criteria with respect to the test airframe structure and the test loading program must be considered [16].

In order to get the best possible correlation between a full scale fatigue test and service usage with respect to beginning and interval of NDI as well as crack propagation behaviour and location of fatigue critical areas a randomized flight-by-flight program with a realistic sequence of load cycles gained out of flight measurements is to be developed and applied [2].

For determining a representative loading program, the following basic requirements should be met:

- Close correlation between the applied loads and their associated stress distributions at all fatigue critical locations
- Simulation of all significant loading conditions and sequences, especially at the fatigue critical locations, for example:
  - . negative loads
  - . gust and maneuver loads
  - . taxi loads
  - . ground to air cycle
  - . empannage laods
  - . flap loads.

For some reasons, especially because of simplification or higher test speed, some parts of the airframe structure are not tested within the full scale fatigue test - for instance empannages are tested separately. On the other hand, certain loads would not be applied correctly for they are not significant for most of the fatigue critical parts - side loads or unsymmetrical loads on fuselage and drag loads on the wing structure are often neglected. In the regions of structural parts which are not loaded representatively and where the combination of the applied external test loads are not correct, fatigue critical parts must be non-destructive inspected. A correlation to future service inspections is impossible. In FIG 2 an example for such a part in pointed out. Other locations to which special attention must be payed in full scale fatigue tests are the external load introduction points. Applied test loads can cause additional significant local stresses because of their more or less point-wise introduction. These locations must also carefully be inspected during the test, but the results also are not transferable to service usage. FIG 3 shows a typical example of a load introduction point NDI.

Normally in the region of fuel tanks high mass loads are to be simulated; therefore the attachment structure must be inspected during full scale fatigue testing.

For the development of NDI procedures it is of great importance that the tested airframe structure is extensively identical with the structure used for the operational aircraft, especially for the fatigue critical locations and their immediate vicinity. For instance, varying skin thickness between the test structure and the structure of the operational aircraft affects the stress distribution as well as the corresponding NDI method. Aircraft in operational usage are often further developed which includes reinforcements of forgings, skins etc. in the fatigue critical areas. In these cases the beginning and the interval of NDI must be determined once more by substituting the altered parts in the full scale fatigue test or by theoretical analysis.

Conditioned by production influences, a scatter of the geometrical shape of the parts must be sometimes included if the NDI method for a fatigue critical location is developed during full scale fatigue tests. FIG 4 shows an example for the adjustment of an inspection procedure to the variable geometry of a part.

Consequently, if during a full scale fatigue test a critical location is realized and a special NDI method is developed for service usage on operational aircraft, a significance check must be carried out. This significance check comprises:

- a check whether the stress distribution due to the test loading program corresponds with the actual stress distribution during flight in order to obtain a sufficient correlation of the initiation and interval of NDI between test and service

- a check whether the geometry of the test airframe and the airframe of the operational aircraft is identical in order to get full agreement of NDI procedure between test and services

- a check whether the NDI procedures cover the full range of production scatter in order to get the optimal adaptation of the NDI procedure during service.

4. NDI METHODS DURING FULL SCALE FATIGUE TESTING AND THEIR TRANSFER INTO SERVICE USAGE

Before putting a full scale fatigue test into operation, a great portion of the fatigue critical areas are principaaly known out of theoretical analysis, component tests and static tests. For these areas detailed ND inspection-plans and NDI surveys can be formed in advance and the NDI procedures can be fitted to the local realities. Some special environmental conditions at the fatigue critical areas which can influence the proposed NDI method often are not simulated within the full scale fatigue test, e.g. moisture in the vicinity of fuel tanks, or hydraulic oil in the main landing gear retraction parts.

During full scale fatigue testing two different basic types of NDI procedures are applied which can be used in service with some modifications:

- continuously recording NDI procedures
- NDI procedures which need an interruption.

In this chapter some special problems and details of NDI procedures during full scale fatigue testing, which have not been in common application until now, and the correlation to service usage are dealt with.

In order to guarantee an uninterrupted running of the test as much as possible, NDI procedures have to be applied which detect and record the crack propagation continuously.

- The method used probably most widely is the application of electrical conductive materials with small cross sections, which are bonded to the structure with adhesive in order to achieve the same relative strain as the structural part. Normally the type of material is copper in the form of a wire (crack wire) or silver in the form of conductive paint.

  The cross sections of crack wires vary about 0.0004 in. and are adapted to the elasticity behaviour of the material. A fully automatic control of a fatigue critical area can be achieved by additional TV monitoring, especially during the phase of fast crack propagation (FIG 5).

  If the electrical conductive material is interrupted by a fatigue crack and a signal is produced, the full scale fatigue test is stopped and the crack length is measured with one or two different NDI methods,because the crack can extend slightly past the conductive material. With this NDI method, fatigue critical areas such as bolt holes, notches, and locations with a high stress level which include also parts with poor accessability (for instance, components such as beams, fittings, etc. in the inner part of a fighter wing) can be controlled. For critical locations existing in large numbers such as rows of bolt holes, special patterns are developed with integrated crack wires. They can be applied to the airframe structure also simply by bonding them with adhesive.

In the scope of new developments, crack wires and conductive paints are applied on fatigue critical areas of aircraft in service usage. With this measure a on condition maintenance is possible for relatively critical structural parts. If the electrical conductive material is interrupted by a crack special devices produce a signal during flight in the cockpit or on ground with the aid or special test equipment.

The reliability of the signals produced by electrical conductive materials can be characterized as sufficient. Nearly all faulty signals which have occured were caused by external influences such as tools, chemical aggressive mediums and so on. Within the reach of small crack length, this means smaller than 0.08 in., reliable results cannot be expected, but an extrapolation of the crack propagation behaviour is possible with the aid of microfractography. To this time, it has not occured whereby a crack crossing an electrical conductive material produced no signal. The conductive paint system compared with crack wire have the advantage of easier repair.

- For specimen tests, continuously operating eddy current devices are used which can be applied on principle to a full scale fatigue test and in the future perhaps to service usage.

- For structural components which can be sealed up a continuous control with regard to crack passing through a part can be performed by pressurisation with a inert medium, mostly gas. Reduction of the initial pressure can be a hint for an existing crack. If a medium is used, which shows a definite color or a characteristic smell,the damaged areas can be located relatively easy. The application of this method is limited to integrally produced or bonded components; built-up structures are mostly not suitable because of possible leakage at fastener holes.

- With continuous stress measurements in highly loaded regions of a structural part and additional measurements in their close vicinity, the existence of a crack can be recognized by a trend analysis showing a redistribution of stress, e.g. decreasing resp. increasing stress values for the same loading condition at different numbers of simulated flight hours (FIG 6).

The most commonly used NDI methods which need an interruption of the test or aircraft service can be classified as follows:

- visual
- eddy current
- ultrasonic
- liquid penetrant
- magnetic particle
- X-ray.

Methods which are at present under development and may play a part in the future are:

- holography
- acoustic emission
- thermal methods.

Generally the requirements of NDI during full scale fatigue testing include the detection of cracks with small lengths as well as determining the crack growth rate in the regions of greater crack length. Normally, no additional environmental influences such as moisture, hydraulic oil and fuel are present during the development of NDI in contrast to service NDI where these influences can cause considerable difficulties. On the other hand, seldom must exact crack growth rates be determined during service usage. Hence, the adjustment procedure for the above mentioned methods during service usage must take place in the direction to detect a definitive crack with a definitive length under environmental influences. In FIG 12 an example for such an adjustment procedure is given.

5. DAMAGES UNDETECTED BY NDI DURING FULL SCALE FATIGUE TESTING

All locations considered as fatigue critical due to theoretical analyses and static and dynamic pretests are collected in an inspection list. In this inspection list the interval and the beginning of inspection as well as the NDI method with which the fatigue critical locations are controlled during the full scale fatigue test are stated. The definition of the practicable NDI method relies considerably on past experience. With this it is possible in certain cases that fatigue damages are not revealed in time because the applied NDI methods are not optimal or the estimated number of simulated flight hours until the beginning of inspection is not correct.

In some cases the most effective NDI method cannot be verified because of time schedule or money limitations. During full scale fatigue testing compromises with respect to the applied NDI method must be concluded in order to get acceptable inspection time to test time relation - i.e.: visual NDI for some regions instead of eddy current or ultrasonic with the result of greater minimum detectable crack length.

Most of the problems arise with the visual NDI methods. FIG 4 shows a typical example of non-optimal visual inspection. Another typical non-optimal NDI method is the use of penetrant inspections for threads, and serrated joints, which had been thought of as a good procedure, until a total failure pointed out their poor qualification for these components (FIG 7). The new NDI method proposed for these parts is an adapted eddy current method.

Within the theoretical fatigue considerations and static tests, some fatigue critical areas are not recognized as being critical. These critical locations are often additionally loaded by secondary bending moments overlayed with the main (tension or compression) loading. In FIG 8 an access cover with the cutout in an upper wing skin is shown; fatigue cracks occured in the radius both of the panel and the skin. The first planned visual inspection was not sufficient and the cracks had a length of about 1.4 in. when they were detected. Afterwards, the NDI method was changed to penetrant with a much more suitable result.

In FIG 9 likewise two fatigue failures due to secondary bending are presented. In the region where the fatigue cracks originated, the lower wing skin is connected with a relatively stiff fitting which ended at that point. The crack propagation was relatively fast and could not be detected by the NDI method (visual inspection) proposed at first. After the first cracks were detected during full scale fatigue test, the NDI method was changed to ultrasonic with crack wire monitoring and TV. The other failure was caused by additional loading in the fuselage skin due to shear buckling at the attachment of the skin to bulkhead.

FIG 10 indicates another group of fatigue cracks which are relatively difficult to detect. In the closed structures of fighter wings, the inner parts can be inspected by NDI in a cursory way without dismantling the total wing skins and beams. As shown in FIG 10 a crack occured in the flange of a servo block covered by the wing skin. The visual inspection was carried out without removing the servo block, because frequent removal of this part (about every 200 simulated flight hours) can cause severe damages in the fasteners holes because of poor fit after several thousands of simulated flight hours. After the lower flange of the servo block was cracked over the whole length, the skin was overstressed and failed as a consequence of the servo block failure. In order to have some indications whether a load carrying inner structure part has failed, torsional and bending stiffness trend analyses can be carried out similar to the previous described strain gauge trend analysis.

Fatigue cracks undetected by NDI can also cause secondary damage. During the crack growth period at fatigue critical locations other parts or locations which are in principle not fatigue critical can be affected by considerably higher stresses due to a redistribution of the stress after the occurance of a crack at the fatigue critical location. FIG 11 shows an example of a bolt which failed repeatedly (fatigue critical part). In the same component a lug (in principal not a fatigue critical part) failed because of the considerably higher stresses encountered during the period between the actual bolt failures and the removal of the bolts. It is therefore necessary to inspect also in the vicinity of fatigue critical locations to determine if a fatigue crack is present and if a significant stress redistribution has taken place.

The fatigue damages undetected by NDI can be found by a carefully performed tear down inspection of all structural parts which are not covered by NDI during the test and by additional destructive inspection. This group of parts exists mainly of components in the inner structure, not accessible for NDI in an assembled condition.

6. COST EFFECTIVENESS CONSIDERATIONS OF NDI FOR SERVICE USAGE

After the development of NDI methods for fatigue critical locations during full scale fatigue testing, an adjustment for using this method in service is necessary. Before taking this step, considerations must be carried out concerning the cost effectiveness of the two alternative possibilities at the moment of beginning of NDI:

- exchange of the part with subsequent overhaul or scrap and replacement by a new or overhauled item (TCI)
- NDI at defined intervals.

The criteria needed to make a decision are:

- the crack propagation behaviour
- the relation between part and removal cost and NDI costs.

In the case of a crack propagation behaviour which implies relatively short NDI intervals it can be advantageous to change the part at the moment of NDI initiation to a new or overhauled one than to inspect with relatively short intervals. An unfavorable crack propagation rate can be caused by a small critical crack length, due to geometrical relations and/or the material properties with respect to fracture toughness.

Especially if extensive and costly removal activities are necessary or if only expensive NDI procedures guarantee the flight safety it must be decided, whether it is better to declare the part in question a time change item. FIG 12 points out a typical part to which the NDI method developed during full scale fatigue test is not applied during service usage, because of cost effectiveness considerations (short inspection intervals because of relatively unfavorable crack propagation behaviour, and relatively great effort for carrying out NDI inspection).

In FIG 13 another group of parts is shown, which must be ND inspected during full scale fatigue testing in order to determine the moment of exchange, but which are not ND inspected during service usage because of their low production cost in relation to the removal/inspection costs.

7. BEGINNING AND INTERVAL OF NON DESTRUCTIVE INSPECTION DURING FULL SCALE FATIGUE TEST AND SERVICE USAGE

The fatigue critical locations defined in component tests and fatigue analyses carried out preliminary to the full scale fatigue test are inspected mostly from the beginning at fixed intervals. The first approach for the interval depends on the assumed crack propagation behaviour at the structural part under consideration. If a fatigue crack is detected it is monitored by shortened intervals in order to get sufficient information for crack growth curves, and sometimes simultaneously monitored by crack wire or TV. If it is likely that the fatigue crack can cause a total failure of the test airframe during the unstable phase, a decision is made whether a repair is to be carried out or the test is to be finished after a failure of the component. The resulting crack growth curves provide in combination with additional specimen tests a basis for an estimation of the initiation and interval of NDI during service usage.

For structures which are designed to be 'damage tolerant' the procedures to determine the inspection intervals for service usage are well known [2, 6, 9, 11, 12, 13].

Since many components and assemblies actually comprise a mixture of safe life and fail safe [4] an approach can be used to calculate the allowable life (economic or safety limit) for the beginning of inspections at the fatigue critical locations during service usage. The applied methods take into account the influence of the material and production process (scatter of strength T_S) if the aircrafts in usage are tracked individually by g-meter and/or fatigue recorder, and additionally the influence of loading (scatter of loading T_L) if the aircrafts in usage are not tracked individually [7, 8].

Out of the scatter factors, with an assumed probability P_A of occurance of a crack at a maximum tolerable length, a safety factor can be calculated which is applied to the mean value of the test results and which leads to the allowable damage index, respectively to the allowable flight hours for NDI. The maximum tolerable crack length depends on the fracture toughness behaviour of the material, the stress condition, the environmental influences, the applied NDI method and the accessibility. The damage index is determined out of the applied stress spectrum by a damage accumulating theory, for instance by means of a Miner calculation [5].

In Fig 14 the procedure for the determination of the beginning of inspection for aircraft in service usage is shown. A convenient value determined out of a great number of tests for the standard deviation of full scale fatigue test results is

$$s_{strength} = 0{,}13 \text{ (scatter } T_s = 1 : 2.15) \quad [15].$$

paired with a probability of occurance for a small crack length $P_A = 10^{-3}$ the safety factor correlated to the mean test result with individual aircraft tracking is in the region of 3 (depending on the number of test results) and in the region of 4 without aircraft tracking.

With the special recording tapes of the fatigue recorders and the forms for the readings of the g-meter, the resulting data can be managed within data processing with a reasonable amount of time and money. If a computed damage index, respectively the number of flight hours accumulated by an individual aircraft, achieves the allowable damage index, respectively flight hours, a NDI must be carried out. An example for the printout of the consumed life and the projected first inspection in flight hours and time schedule for logistic handling is shown in FIG 15.

The inspection intervals during service usage can likewise be determined damage equivalent. Otherwise, the factored number of test hours between the beginning of inspection and the unstable crack growth/failure must be divided by the number of necessary inspections to detect the crack with a high degree of confidence [15].

8. EVALUATION OF NDI RESULTS

In order to get the full information for a certain component concerning its fatigue behaviour it is necessary to evaluate all results of service ND inspection [11]. Besides the general data of the individual aircraft and the damaged component, e.g.

- aircraft serial number
- part number and serial number of damaged part

information concerning the reasons which caused the failure and the specific failure data must be tracked:

- relevant number of flight hours/landings
  . accumulated flight hours, landings etc.
  . accumulated damage index, spectrum type
- type of defect or failure
  . crack (position, length)
  . type of failure (fatigue, corrosion, stress, overload or combination of these)
- material and manufacturing data
  material, manufacturing process, heat treatment, surface treatment
- stress conditions
  . geometry, stress concentration factor
  . nominal stress

A proposal for a data collection sheet which is data processing compatible is shown in FIG 16. These data are the basis for corrections of the beginning and intervals of NDI. They also can be used as a control of the success of the applied NDI method.

9. CONCLUSION

A full scale fatigue test can be a powerful tool for defining efficient NDI at the fatigue critical locations if some criteria are considered concerning the loading program, the significance of the stress distributions, and the test specimen itself. In combination with an individual aircraft tracking program, the full scale fatigue test results allow the application of the most efficient NDI to each aircraft in service and to each critical location individually.

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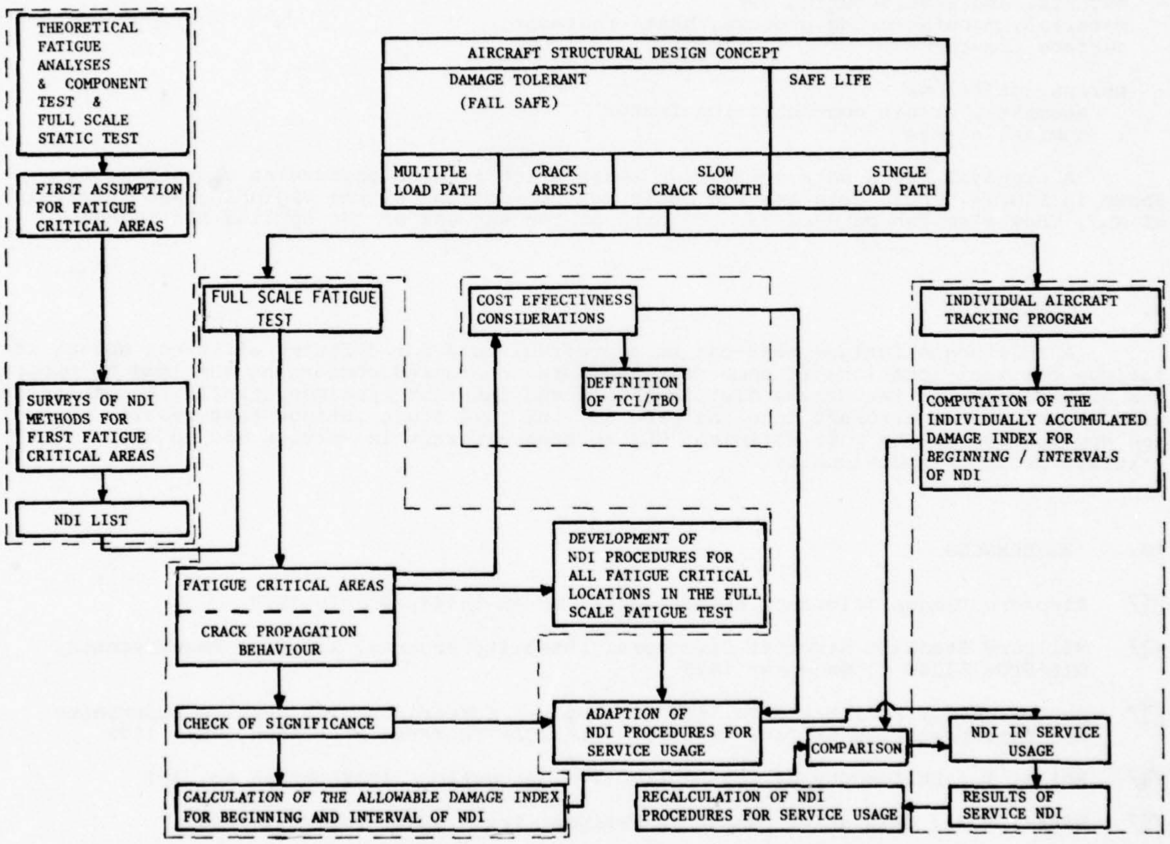
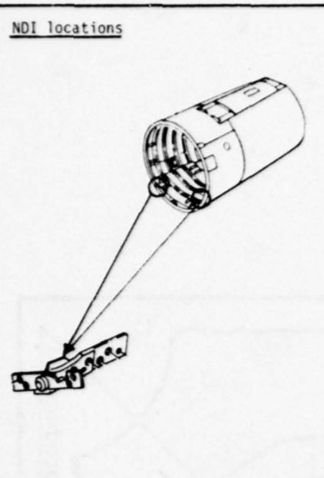
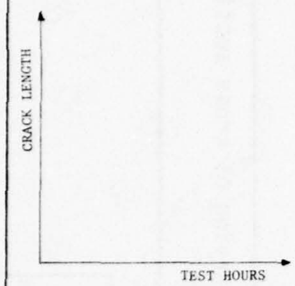


Fig.1 Basic procedure for the development of NDI procedures

NDI LIST FOR FULL SCALE FATIGUE TEST	FIGHTER A/C	POSITION NO. 12

NDI locations





O LOCATION IN FIRST NDI SURVEY

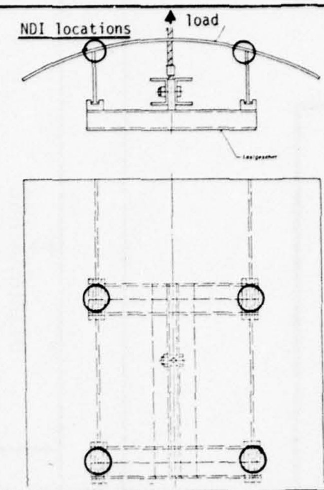
□ *ADDITIONAL LOCATIONS DURING* FULL SCALE FATIGUE TEST

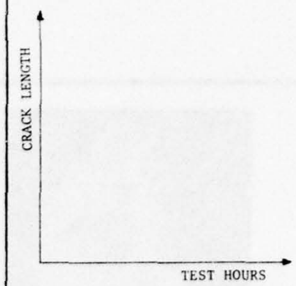
Part description	attachment fitting empannage
Parts to remove for NDI	none
NDI method	visual
Beginning of inspection	5oo test hours
Inspection interval	2oo test hours
Test results	-
Type of damage	fatigue crack in the tack weld
Number of test hours	crack length
1 800	.1 /in/
Part removed after	1 800 test hours
Significance check	negative
Stress distribution	-
Geometrical properties	-
Adaption of full scale test NDI procedure to service usage	negative
remarks	too high shear loads applied

Fig.2 Example for NDI at empannage at attachment fitting

NDI LIST FOR FULL SCALE FATIGUE TEST	FIGHTER A/C	POSITION NO.34

NDI locations





O LOCATION IN FIRST NDI SURVEY

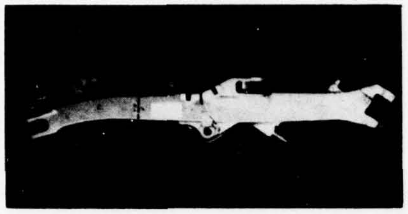
□ ADDITIONAL LOCATIONS DURING FULL SCALE FATIGUE TEST

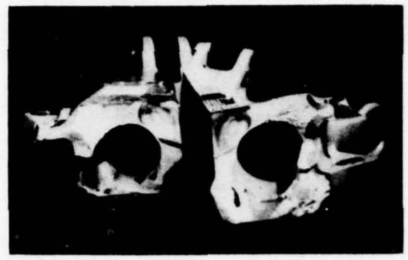
Part description	load introduction point No. 11
Parts to remove for NDI	tank area
NDI method	visual
Beginning of inspection	400 test hours
Inspection interval	400 test hours
Test results	
Type of damage	none
Number of test hours	crack length
-	-
Part removed after	- test hours
Significance check	negative
Stress distribution	-
Geometrical properties	-
Adaption of full scale test NDI procedure to service usage	negative
remarks	

Fig.3 Example for NDI at a load introduction point

EVENT: Fatigue Failure of a Forged MLG

Fatigue Critical Location





FIRST PROPOSED NDI: Visual with Microscope

POSSIBLE NDI	ADVANTAGE	DISADVANTAGE
VISUAL	quick, not costly	crack detection difficult
X-RAY	good documentation test results	inspection difficult because of varying material thickness, high effort of apparatus
ULTRASONIC	registration of flaws in the material	bad accessibility for ultrasonic
EDDY CURRENT	simple handling, reliable readings even with varnish	special adapters for changes in shape

SELECTED NDI: Eddy current with special adapter for varying of cross section shape due to production process (forging)

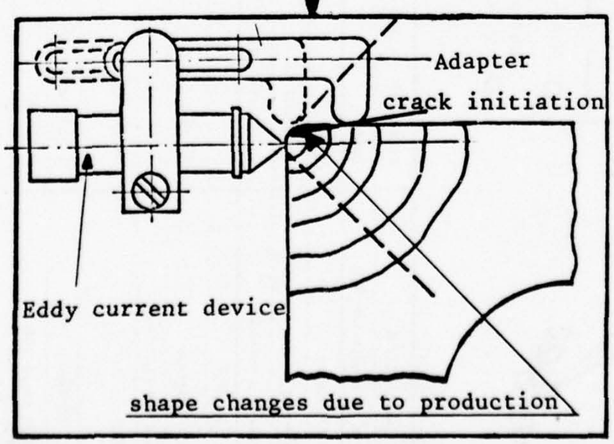


Fig.4 Selection of a NDI procedure and adaption to production scatter

Fig.5 Monitoring of a fatigue critical location with crack wires and TV

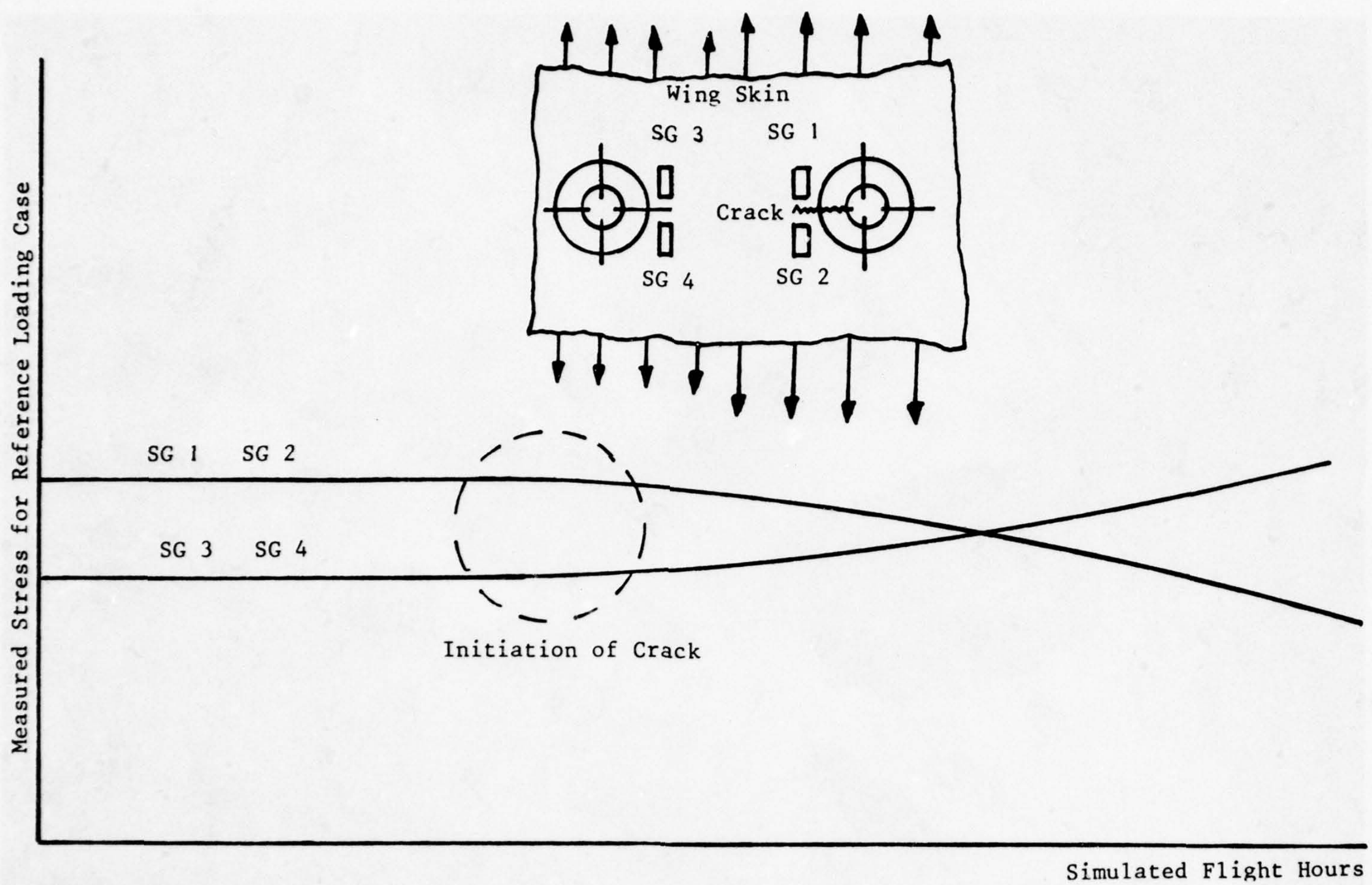


Fig.6 Stress trend analysis

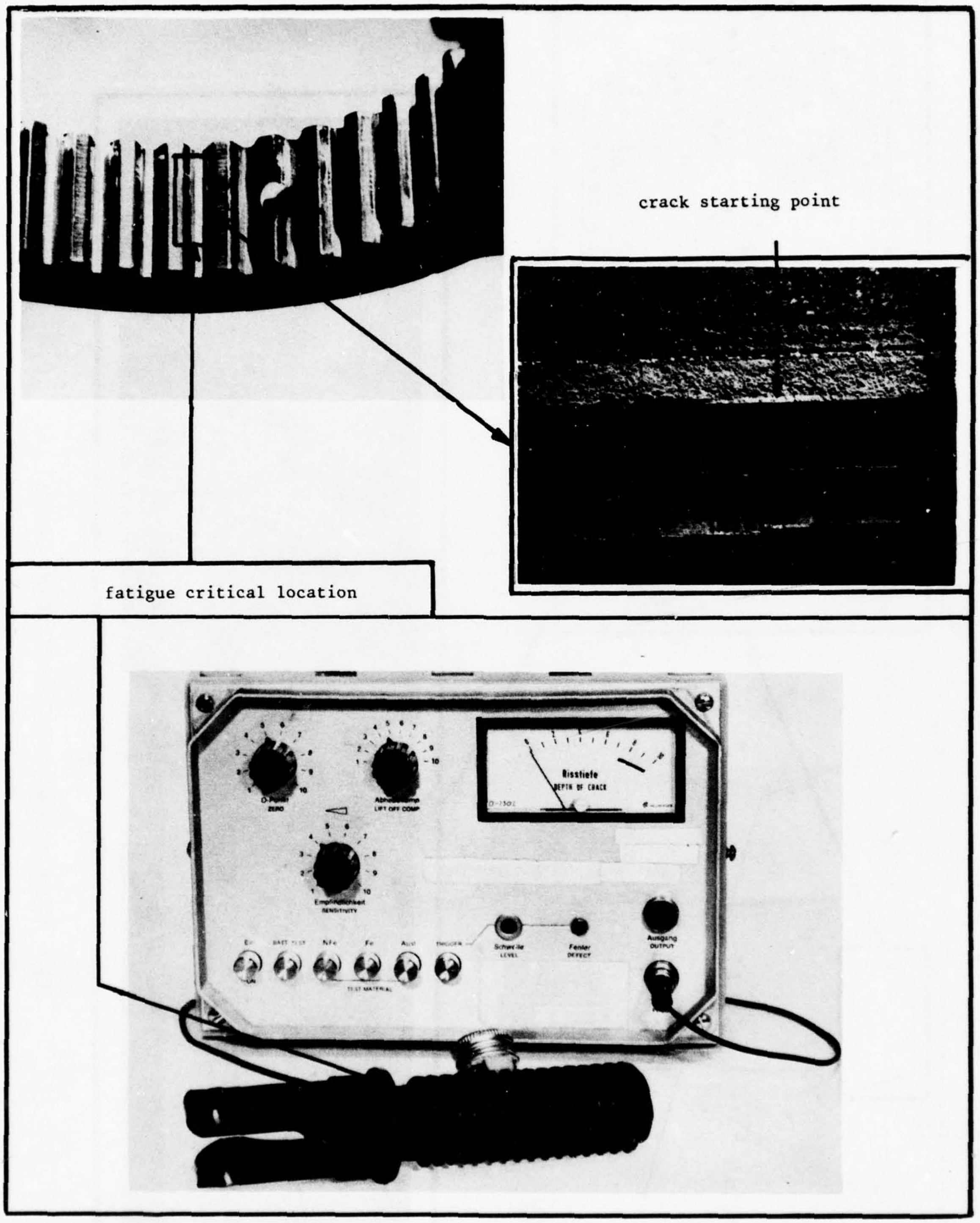


Fig.7 Eddy current NDI for separated joints (top) and threads (below)

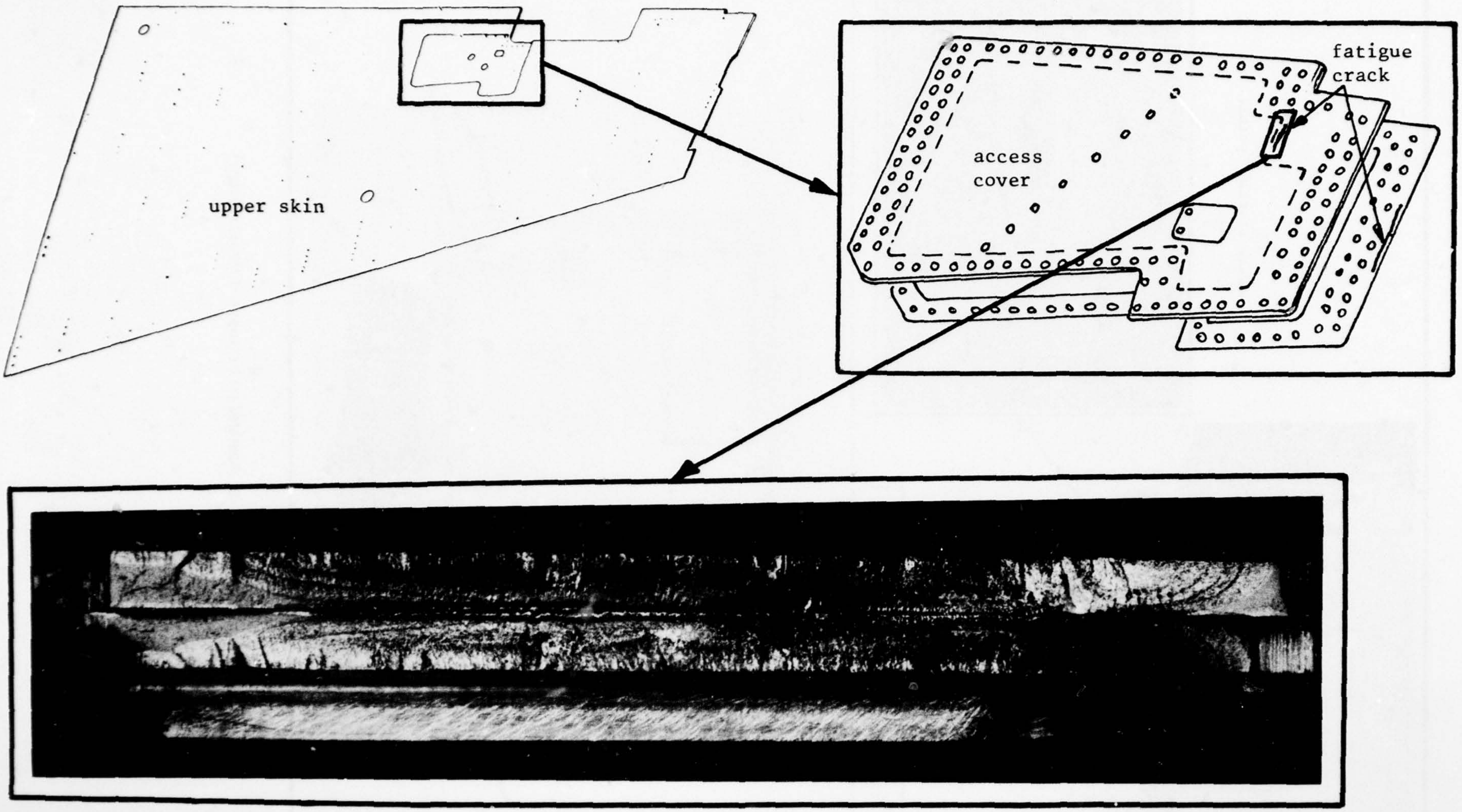


Fig.8 Fatigue cracks in an access cover of an upper wing skin

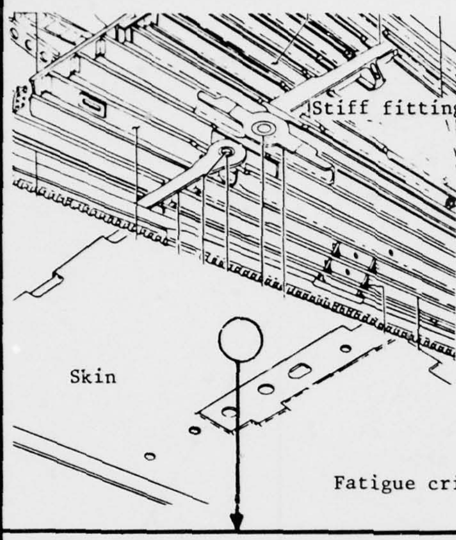
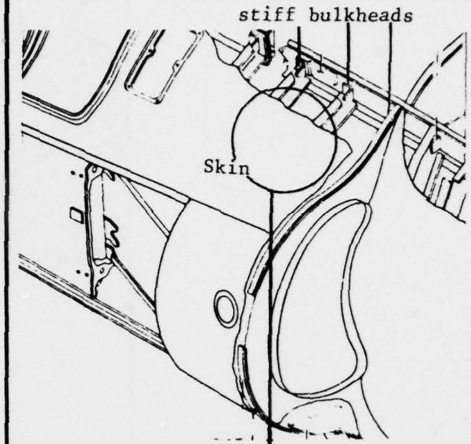
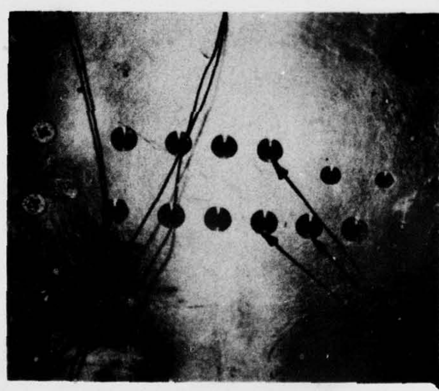
MAIN COMPONENT	WING	FUSELAGE
FATIGUE CRITICAL AREA		
	Fatigue critical location	
	lower wing skin at the pylon fitting attachment	fuselage skin at the bulkhead attachment
		
	Cracks	
LOADING CONDITION PRIMARY	tension (wing bending)	shear
SECONDARY	bending (stiffness change)	bending (buckling at stiffness change)

Fig.9 Fatigue failures due to additional loadings

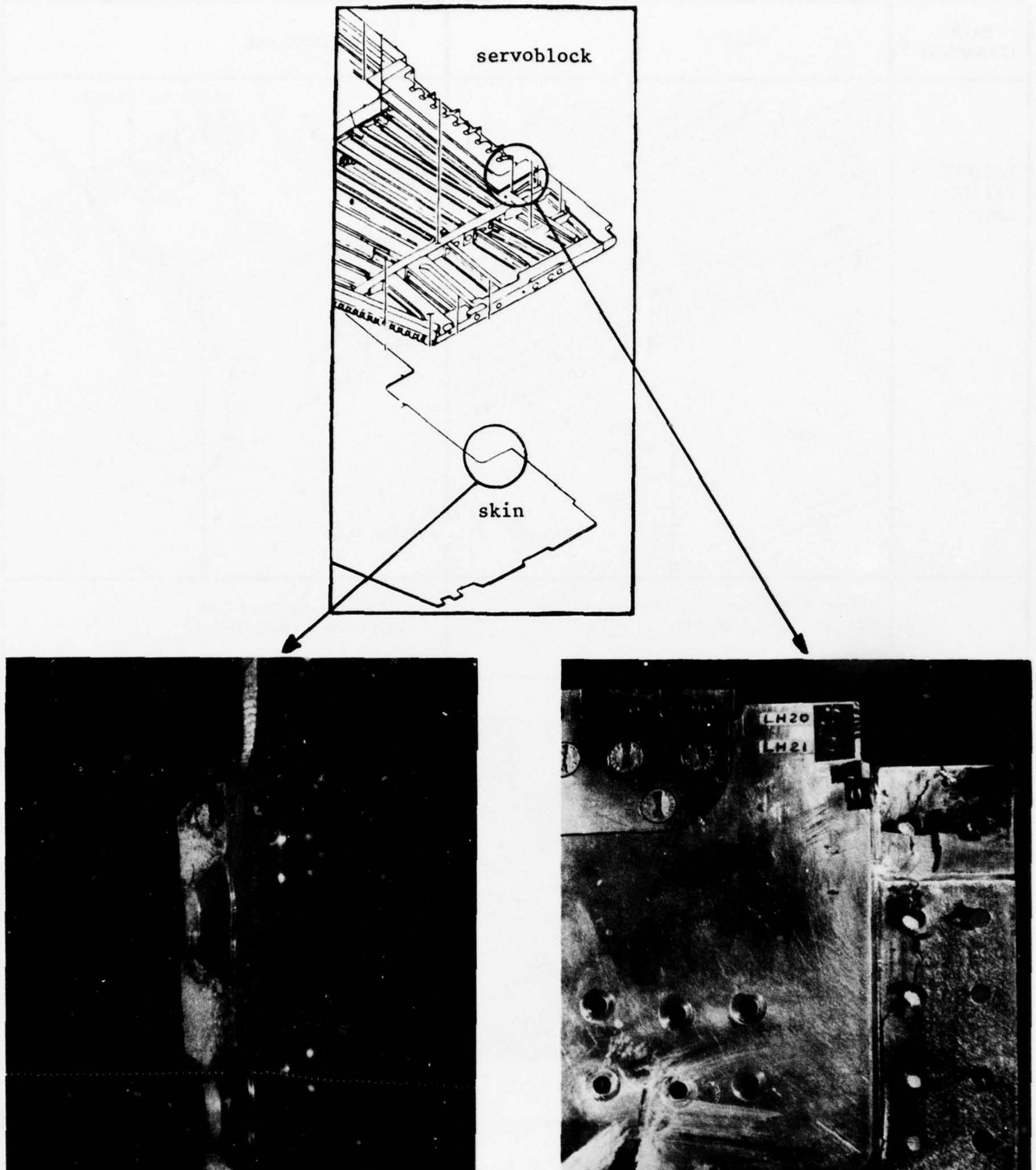


Fig.10 Fatigue failures on inner wing structure

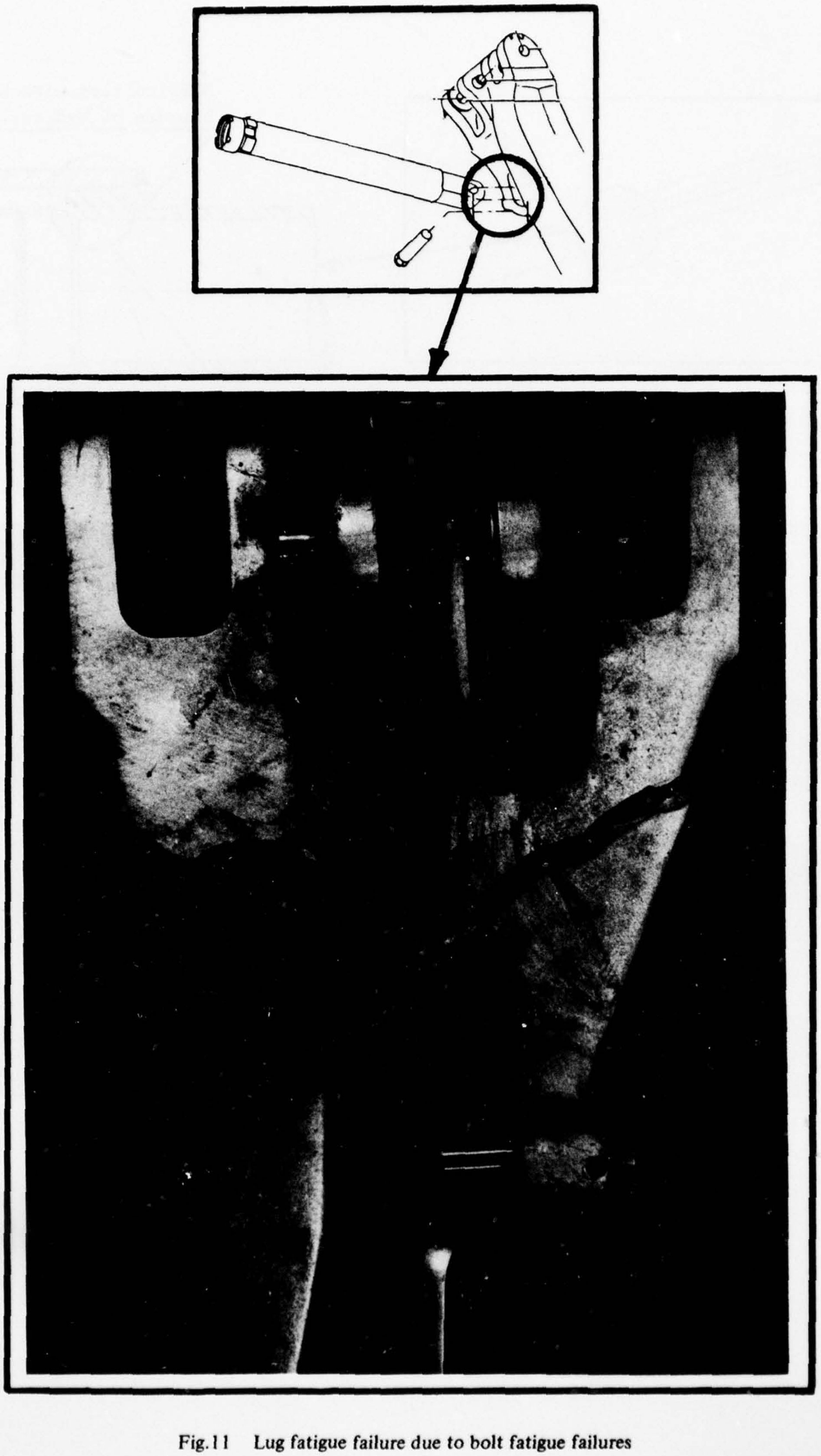


Fig.11 Lug fatigue failure due to bolt fatigue failures

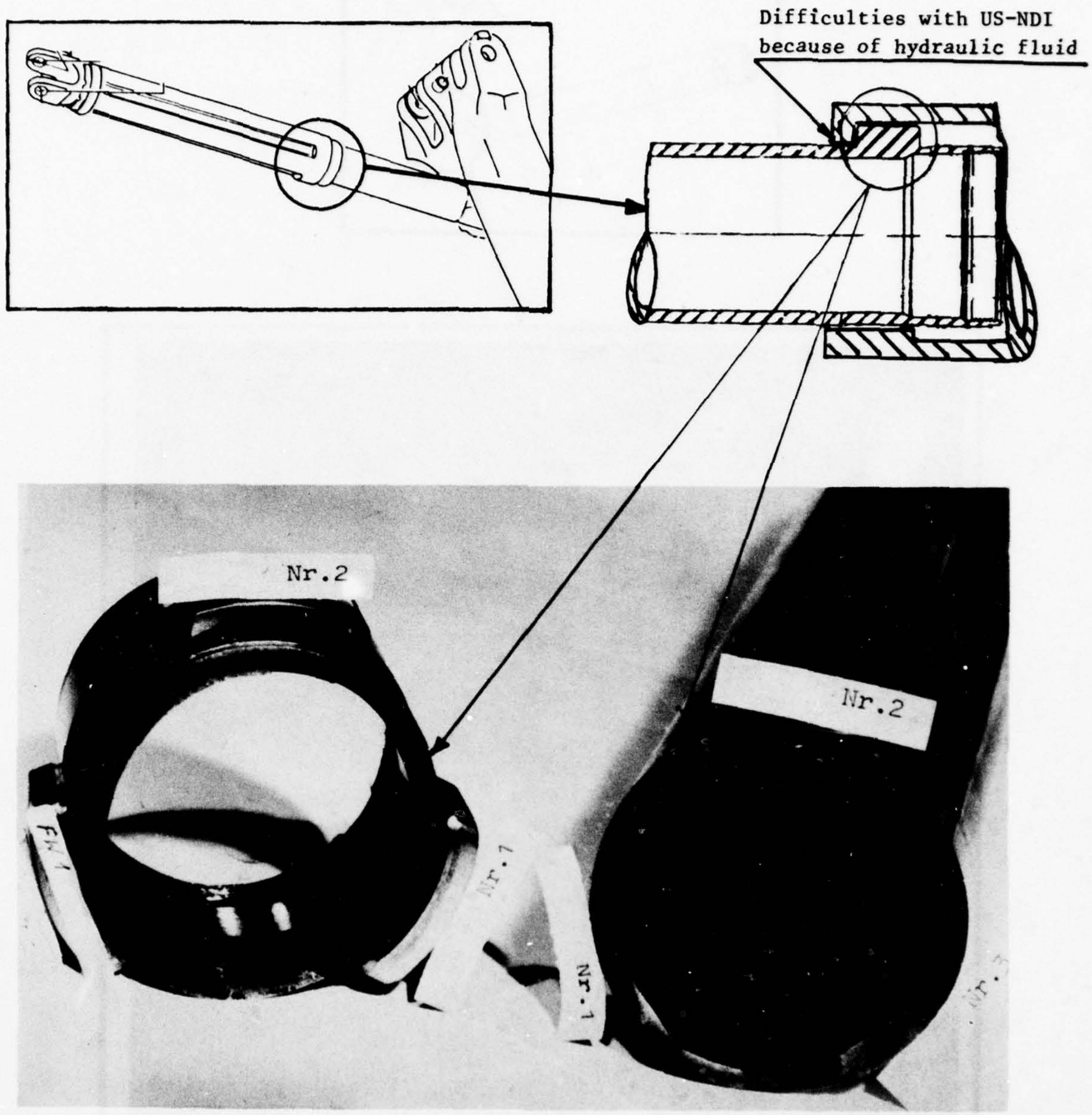


Fig.12 Fatigue critical location on a drag strut

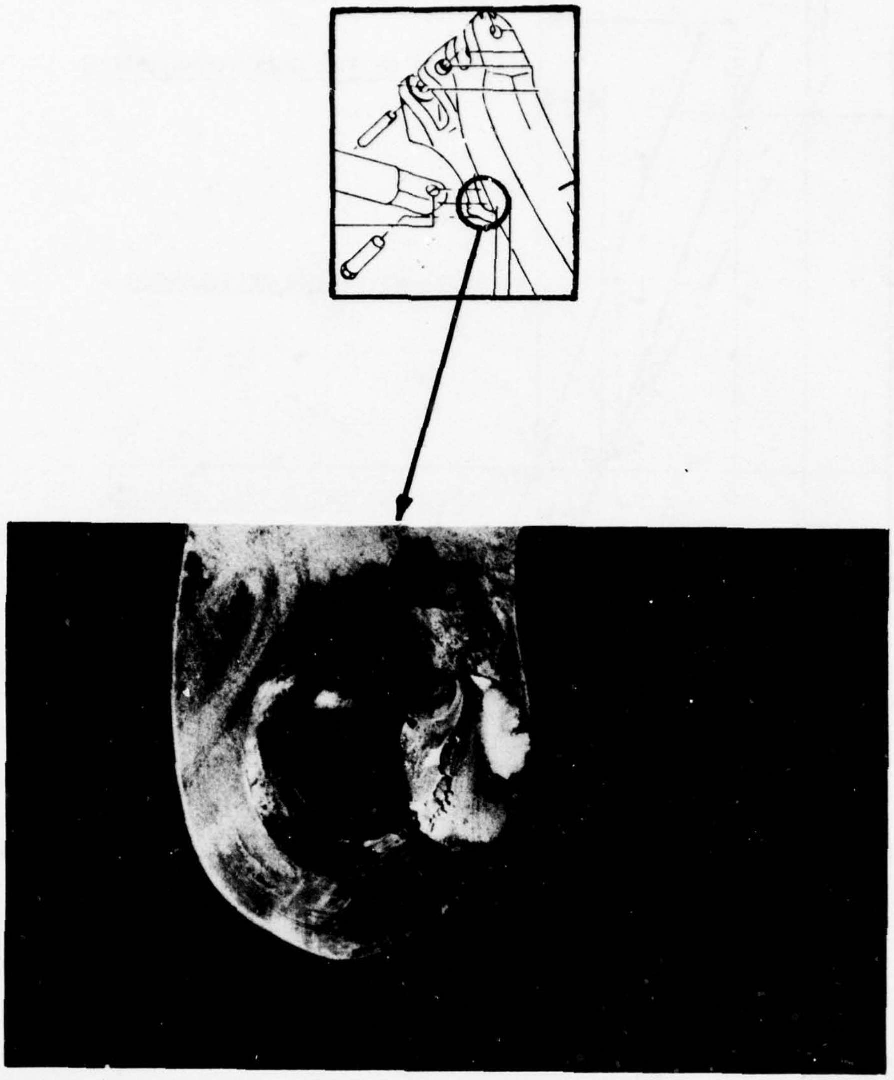


Fig.13 Fatigue failure of a bolt

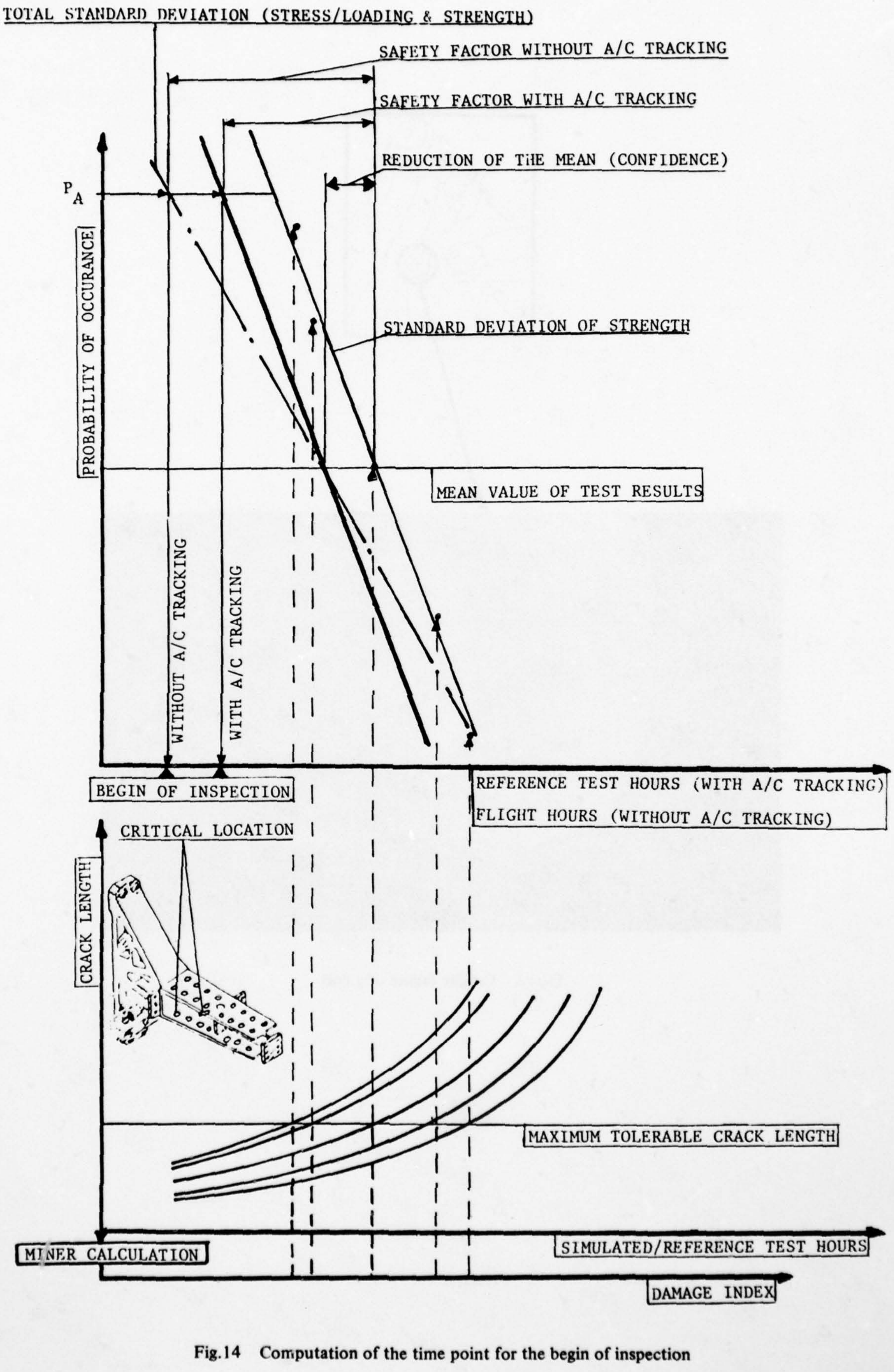


Fig.14 Computation of the time point for the begin of inspection

WING NO. 55
CRAFT AIRFORCE BASE

NO.	AIRCRAFT	SERIALNUMBER RH-WI	SERIALNUMBER LH-WI	TOTAL FLIGHT HOURS FUSL.	TOTAL FLIGHT HOURS RH-WI	TOTAL FLIGHT HOURS LH-WI	DAMAGE IN PERCENT FUSL.	DAMAGE IN PERCENT RH-WI	DAMAGE IN PERCENT LH-WI	REMAINING HOURS UNTIL SCRAP FUSL.	REMAINING HOURS UNTIL SCRAP RH-WI	REMAINING HOURS UNTIL SCRAP LH-WI	REMAINING HOURS UNTIL INSPECTION RH-WI	REMAINING HOURS UNTIL INSPECTION LH-WI	FIRST WING MONTH/YEAR INSP.	FIRST WING MONTH/YEAR SCRAP
1	161	1068	1052	2556	395	395	84.04	72.29	72.29	448	151	151	36	36	2/77	9/77
2	1110	1018	1018	2661	559	559	82.44	71.92	71.92	521	218	218	54	54	3/77	12/77
3	1116	1083	1076	2432	151	517	75.42	24.74	69.74	715	458	224	330	68	4/77	1/78
4	1100	1121	1060	2444	604	604	73.02	69.25	69.25	948	268	268	84	84	5/77	3/78
5	1069	1014	1075	2786	474	474	88.37	65.54	65.54	297	249	249	97	97	6/77	2/78
6	962	1078	1078	2221	546	546	66.50	62.50	62.50	1163	328	328	143	143	8/77	6/78
7	1097	963	1113	2576	414	414	79.32	56.08	56.08	630	324	324	168	168	10/77	6/78
8	978	1049	962	2221	406	406	68.46	53.87	53.87	933	348	348	189	189	11/77	7/78
9	1093	960	1125	2010	433	433	60.99	54.61	54.61	1279	360	360	193	193	11/77	8/78
10	1104	1107	963	2524	383	383	78.58	52.47	52.47	594	347	347	193	193	11/77	7/78
11	159	1116	987	2501	423	423	73.47	53.63	53.63	935	366	366	199	199	11/77	8/78
12	1003	1093	1017	2212	204	204	71.60	39.58	39.58	563	311	311	202	202	12/77	5/78
13	1096	1024	975	2706	403	403	83.01	50.89	50.89	515	389	389	222	222	1/78	10/78
14	1049	1029	1086	2143	381	381	64.83	49.16	49.16	1173	394	394	231	231	1/78	10/78
15	979	159	1082	2644	422	422	79.17	50.70	50.70	759	410	410	235	235	1/78	11/78
16	996	1082	1071	2619	532	532	78.08	52.79	52.79	790	476	476	263	263	3/78	2/79
17	1068	1016	1098	2524	375	375	77.30	46.14	46.14	696	438	438	266	266	3/78	12/78
18	1024	1013	1107	2242	224	224	69.98	34.64	34.64	807	422	422	286	286	4/78	12/78
19	983	992	1065	2492	270	270	75.96	35.91	35.91	749	482	482	323	323	6/78	3/79
20	1014	1003	1012	2732	177	177	84.93	27.39	27.39	389	470	470	333	333	7/78	2/79
21	1017	1002	1009	2773	78	78	84.02	14.29	14.29	527	466	466	351	351	8/78	2/79
22	977	1102	1105	2139	179	422	63.70	19.82	42.60	1326	726	569	535	360	8/78	8/79
23	992	421	460	2349	108	108	73.67	18.12	18.12	650	490	490	364	364	8/78	3/79
24	475	1086	1046	2424	79	79	78.19	13.51	13.51	450	504	504	381	381	9/78	4/79
25	1002	987	1059	1750	92	92	53.45	14.68	14.68	1442	535	535	402	402	10/78	6/79
26	1121	1006	1077	2482	177	177	75.50	19.83	19.83	767	716	716	527	527	5/79	4/80
27	1063	999	1013	2660	287	287	79.05	27.14	27.14	858	770	770	547	547	6/79	7/80
28	1154	1054	1110	2598	343	343	77.92	28.98	28.98	758	840	840	591	591	9/79	10/80
29	1019	1006	966	2321	266	266	65.15	12.12	12.12	1289	835	835	634	634	11/79	10/80
30	977	966	1115	1865	89	89	57.35	11.65	11.65	1271	839	839	639	639	11/79	10/80

TIME TABLE OF ACTIVITIES

YEAR	BEGINNING OF INSP. 1K QUARTER 1	QUARTER 2	QUARTER 3	QUARTER 4	YEAR TOTAL
1975	0	0	0	0	0
1976	0	0	0	0	0
1977	2	3	1	6	12
1978	5	2	4	1	12
1979	0	2	1	2	5
1980	3	13	0	0	16
1981	0	0	0	0	0
1982	0	0	0	0	0
1983	0	0	0	0	0
1984	0	0	0	0	0
1985	0	0	0	0	0
1986	0	0	0	0	0
1987	0	0	0	0	0
1988	0	0	0	0	0
1989	0	0	0	0	0
1990	0	0	0	0	0
1991	0	0	0	0	0
1992	0	0	0	0	0
1993	0	0	0	0	0
1994	0	0	0	0	0
1995	0	0	0	0	0
1996	0	0	0	0	0
1997	0	0	0	0	0
1998	0	0	0	0	0
1999	0	0	0	0	0
2000	0	0	0	0	0
2001	0	0	0	0	0
2002	0	0	0	0	0
2003	0	0	0	0	0
2004AF	0	0	0	0	0
TOTAL					45

Fig.15 Example for the printout of the computed time point for NDI and scrap

0	Number of data collection sheet Date		89
1	Type of aircraft	+	fighter a/c
2	Main component	+	WAF # 5
3	Part description P/N S/N		 123456-7 890123-4
4	Material / treatment		7075T6
5	Accumulated flight hours		2260
6	Accumulated damage index		0.112
7	Type of defect or failure	+	fatigue crack
8	Location of failure / dimension	+	bolt hole No. 12/1.2
9	Stress situation σ maximal K_T spectrum index	+	 14 3.6 2
10	Taken measures	+	replacement
11	NDI procedure / TA	+	eddy current TA 123
12	Number of NDI carried out		2
13	Number of NDI appliance		123 / 456 - 78
14	Recalculation of initiation interval NDI procedure necessary	+	 no no no
15	Revision of NDI appliance nessary	+	no

\+ see index list for code numbers

Fig.16 Proposal for an inspection data collection sheet

CRITICAL INSPECTION OF BEARINGS FOR LIFE EXTENSION

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Background research with the object of developing more definitive nondestructive inspection methods for improved reliability and quality of rolling element bearings is reviewed. The primary thrust of the research has been directed at the inspection of precision mainshaft and transmission bearing assemblies in which the individual components -- outer race, rolling elements (balls or rollers) and inner race -- can be separated, readily. Typical results obtained with magnetic perturbation for flaw detection, Barkhausen Noise Analysis for residual stress assessment, and laser scattered radiation for surface finish and surface anomaly detection are presented. The Critical Inspection of Bearings for Life Extension (CIBLE) program concept is described; a cardinal element of this program is the examination of new and used bearings, installation of the bearings in gas turbine engines, re-examination of bearings at engine overhaul and the development of serviceability criteria based on actual service performance of the bearings in engines, and a determination of the correlation between the nondestructive inspection signatures and the bearing serviceability criteria. The preliminary phase of the program and the development of semi-automatic equipment for data acquisition and analysis are described, together with recent applications.

I. INTRODUCTION

A computer-assisted automatic system for quantitative nondestructive evaluation/inspection of ball and roller bearing components has been developed and is now being integrated into bearing inspection processing at the Corpus Christi Army Depot and the Air Force Logistics Center at Tinker AFB in Oklahoma City. A similar system is being used at Southwest Research Institute for bearing investigations and also in the CIBLE (Critical Inspection of Bearings for Life Extension) program.

The primary purpose of the CIBLE program is to provide significantly improved nondestructive methods for inspecting new and used bearing components to ensure a high degree of uniformity and reliability and to provide a basis for forecasting bearing life based on measured material conditions of individual bearing components, i.e., inner race, outer race, balls/rollers as shown in Figure 1. Technical foundations for the methods (1-24) and a concise summary of the CIBLE concepts (25) have been presented previously, but a brief review is presented below. A cardinal element of the program is the acquisition of a comprehensive data base from a large fraction of several selected in-service bearing populations (for example, J57 engine main shaft No. 4 position ball bearing) before service and at subsequent intervals during the service life. Computer processing of the extensive data acquired (from components of individual bearings) will aid in development of trend analyses based on characteristic signature changes associated with service-induced bearing deterioration or changes which ultimately result in failure of the bearing component. The service data base will be supplemented by metallurgical investigations and controlled endurance testing investigations of selected service components. Use of actual engine service instead of the usual laboratory endurance testing ensures realistic conditions and also eliminates the unacceptable high cost associated with testing large numbers of main shaft bearings for times commensurate with actual service times. Ultimately a serviceability criteria will be evolved based on computer assisted multiple parameter analyses to establish correlations of the individual bearing data profile with bearing performance in actual service.

Since only a very small fraction of bearings fail from material conditions, it is necessary to examine a large number of bearings. At the present time, the data base is not sufficiently extensive to permit even a preliminary forecast. Furthermore, an extended program (5 years or longer) is required because it is necessary that data be acquired from bearings at one or two successive overhaul intervals. However, as anticipated, the extensive high sensitivity, high resolution data acquired during routine high-speed inspection of bearing components has disclosed examples of imperfections in new, used and reprocessed bearing components which should be of concern to the user.

II. BRIEF REVIEW OF MAGNETIC NONDESTRUCTIVE EVALUATION METHODS

Magnetic methods are among the oldest of nondestructive approaches. The most commonly used approach is, of course, magnetic particle method wherein flaws are indicated by the accumulation of particles attracted to the magnetic poles formed by discontinuities. There are, however, other magnetic methods which have potential for application to a wide range of specialized problems.

The physical basis for the magnetic properties of ferromagnetic materials is best described by the magnetic domain theory. This theory which now has comprehensive experimental confirmation, postulates that the material is comprised of local regions called ferromagnetic domains, each magnetized to saturation, but aligned according to the state of local magnetization. Adjacent domains are separated by a thin, highly localized magnetic transition region called a domain wall or Bloch wall. Even in the demagnetized state, all domains are still magnetized to saturation, but the orientation of the individual domain magnetization vectors is random, which results in the net magnetization of the specimen being 0. The application of a magnetic field or a stress can change the configuration of the domains, principally by wall movement.

Investigations have confirmed that with carefully prepared specimens, usually single crystals, it is possible to calculate domain wall positions and configurations based upon minimum energy consideration. Magnetic pole distributions around inclusions have been calculated and experimentally observed. However, with complex shape polycrystalline specimens and engineering components, precise calculations based on domain interactions have not been accomplished.

The fact that magnetic domain walls can be forced to move under the influence of a changing applied magnetic field or stress, provides the fundamental basis for the Barkhausen noise method of nondestructive residual stress measurement. Barkhausen, in 1917, discovered that voltages induced in an electrical coil encircling a ferromagnetic specimen produced a noise when suitably amplified and applied to a speaker, even though the magnetization applied to the specimen was changed smoothly. We now recognize these small discontinuous increments as Barkhausen jumps, which are caused principally by discontinuous movements of mobile magnetic boundaries between adjacent magnetic domains and occasionally by the initiation of new magnetic domain walls. The direction and magnitude of the mechanical stress existing in a macroscopic ferromagnetic specimen strongly influences the detailed dynamics of the domain wall motion and correspondingly influences the Barkhausen noise. Advanced magnetic evaluation methods had their beginning at Southwest Research Institute in the early 1960's when an industrial client contracted to develop more sensitive methods for subservice flaw detection in bearing components. Subsequently the work has been extended to the early detection of fatigue damage and more recently to the measurement of residual stress using the Barkhausen noise phenomenon. The research has been concerned primarily with the detection of very small flaws and small fatigue cracks. Conventional nondestructive methods have been effective in the range from approximately .05 to .25 inches and larger. The advanced magnetic methods have been useful in detecting fatigue cracks with a minimum size of approximately 0.003 inches and under some conditions, for example in ball bearing components, inclusions as small as 0.001 inches in diameter have been repeatedly and reliably detected.

A relatively simple analytical model has shown that the magnetic field in the vicinity of the inclusion or flaw can be predicted to provide a basis for experimental determination. The predicted magmetic field shows that the separation of the peaks in the magnetic field component perpendicular to the surface containing the flaw will be approximately equal to the distance from the surface to the centroid of the flaw itself. These elementary calculations have been helpful in guiding the experimental work and in the interpretation of experimental results.

An experimental investigation of fatigue damage mechanisms and nondestructive fatigue damage detection methods has been carried out using specimens which are conventional rod-type tension specimens, containing no notches with surfaces which are carefully finished to remove all machining and grinding marks. Typically, data are acquired at relatively high and relatively low magnetic flux densities by scanning a small magnetometer along the longitudinal axis of the specimen. The magnetometer is a haul-effect probe with minute sensing element approximately 0.001 inches by 0.004 inches, thereby providing very high resolution. Data are obtained before cycling and at selected intervals during cycling. The specimen is monitored continuously by means of six ultrasonic surface wave transducers operating at 10 megahertz.

Success of the magnetic methods in providing NDE measurements of critical importance in determining the material performance of bearings has provided the technical basis for significantly improved nondestructive evaluation procedures. The next section gives a brief description of the NDE equipment which has evolved and preliminary but important results which have already been obtained will be presented.

III. EQUIPMENT

The CIBLE equipment provides a completely integrated nondestructive inspection methodology using non-contacting sensors with precision tracking of individual probes. Accordingly, it is possible to correlate results from several sensor channels, thereby providing a basis for more completely defining and quantifying signature sources. Sensitive quantitative nondestructive examinations of the active race and ball/roller surfaces of individual ball and roller bearing components are accomplished rapidly and automatically under the supervision of a minicomputer. Three different NDE methods are used; namely, magnetic perturbation, Barkhausen noise analysis and scattered laser radiation. A photograph of the overall system is shown in Figure 2. The computer, data terminal, magnetic recorder, power supplies, electronics, etc., are housed in the center consolves; the inner and outer race inspection module is in the cabinet at the left and the ball/roller inspection module is in the cabinet at the right for the Air Force System.

A photograph of the race inspection assembly is shown in Figure 3 and Figure 4 is a view of the ball/roller inspection assembly. Precision fixtures and associated software are required for each different configuration component; change-over from one configuration component to another is simple and can be accomplished in approximately 5 minutes. Fixtures, essentially, consist of precision air-operated chucks for positioning the bearings during inspection and magnetic pole pieces to guide the flux to the inspection region. The pole pieces also support and precisely position the magnetic perturbation and Barkhausen probes which are air-cushion floated on the race surface. Stepper motors under supervision of the computer automatically index the probes to inspect the active raceway surfaces during high-speed rotational scans of the bearing component. An optical sensor acquires a permanently engraved reference mark on a non-critical surface of the bearing race and this mark is tracked continuously by the computer to provide precise signature azimuthal information. The laser inspection requires no special fixtures and only a software change is required to accommodate different components. After the inspection is completed, the components are automatically demagnetized. Signature information is stored in the computer memory during inspection and printed out on a teletype terminal or other high-speed recorder after completion of the inspection. A fixture is also provided which permits precise location positioning of signature regions in the field of view of a microscope; a camera attachment facilitates photographing the surface. All inspection parameters, for example rotational speed, positioning sequences, magnetic field sequences, etc., are automatically controlled by the computer during inspection. Figure 5 is a system diagram and the black lines indicate routine functions of the operator; a teletype terminal is used for operator-computer communication.

Selected equipment features and a concise summary of the inspections performed are presented in Table 1. One of the magnetic inspection examinations is capable of resolving minute subsurface inclusions as small as 0.001 inch (0.025 mm) in diameter which is far beyond the capabilities of other nondestructive inspection methods. During the laser scan the total active surface of the raceway is examined as compared to isolated tracks normally examined with conventional surface-roughness measuring devices. The Barkhausen noise analysis method of residual stress measurement is a state-of-the-art development capable of sending subsurface stress changes caused by service (26) and associated material transformations which occur during extended severe loading of ball bearing components; this is the only known, completely nondestructive method of sending such stresses.

Each set of fixturing includes a reference bearing component used to check overall function of the equipment at intervals. The hard copy printout and Polaroid photographs of actual signatures obtained from such a component are presented in Fig. 6. Test flaws are a lapped hole (a geometric void simulating an inclusion) and a mechanical indent, (a very shallow geometric void but is a pronounced localized surface contour change and, furthermore, localized stresses and strains are associated with the indent.)

The characteristic signatures obtained with circumferential flux orientation are shown in Figure 6A.

The signatures presented in Figure 6B were obtained with radial flux orientation and the change in localized surface contour is the primary factor influencing these signatures.

In the present equipment configuration, the residual stress measurement is not made in a scanning mode but at selected locations including the center of the load track and at locations near the extremeties of the load track. Characteristic Barkhausen signatures obtained from the reference component are shown in Figure 6E. The two signatures shown were obtained from the same location but on successive cycles of the magnetic field sweep. This characteristic shape is obtained from races with high residual compression stresses; low amplitude signatures are obtained from tension regions. Usually for material in tension, the signature consists of a leading edge spike followed by a triangular shaped segment and examples are presented in a later section.

Laser signatures are presented in Figure 6C for the pit or surface anomaly inspection mode and for the surface finish mode in Figure 6D. The characteristic spike signatures for the surface anomaly inspection mode are influenced by several different parameters. In the surface finish inspection mode the upward departure of the signal trace from the baseline is associated with increasing surface roughness of the component.

IV. RESULTS

A. Surface Flaws

In Figure 7 characteristic signatures obtained from new mainshaft bearing inner races (for the number two position in the J85 engine) are shown in the 35mm recordings obtained during one revolution of the bearing; the associated expanded sweep Polaroid photos, along with photographs of the surface flaws which caused the signatures are presented also. These signatures were obtained with circumferential high-field (CH) inspection conditions. The signature at the left from bearing Serial No. 07219 is relatively symmetrical in the left-to-right scan direction. In contrast, the signature at the right from bearing Serial No. 05672 shows an asymmetry which corresponds qualitatively with the asymmetry of the flaw as seen in the surface photograph.

It has been confirmed that spalling type failures can often originate at indentations during

laboratory endurance testing of bearing components and an excellent example illustrating this type failure is shown in Figure 8. The indent is the small, irregular shaped impression touching the extreme left edge of the spall and indicated by an arrow. At higher magnification, the grinding lines were still evident in the bottom of the indent and this characteristic condition is evidence that the lubrication film existed at the time this indent was embossed in the surface during running of the bearing. In the absence of the lubricating film, the grinding lines are obliterated by relative motion between the two contacting surfaces as the embossing action occurs.

Characteristically, the indent is observed on the leading edge of the spall and, in the illustration presented, the ball would roll from the left to the right edge of the illustration. Another feature is that the numerous small indents on the ball exit side of the spall are caused by debris particles from the spall development. Also, a characteritic sheen or smooth texture exists in a narrow region surrounding the indent.

During the routine automatic inspection of new J57 engine bearings, signatures have been obtained in a number of instances from indents. A selected example from a new J57-#4 position outer race is shown in Figure 9. Note at the upper left that the computer printout indicates a flaw signature obtained at radial high-field (RH) conditions on Track 0007 (this is in the load track region during operation of this bearing) and located at 2792 counts from the reference "0" mark on the bearing. The fact that no circumferential printout is obtained indicates that the flaw is very shallow. A Polaroid photo showing the actual signature and a surface photograph located coincident with the signature are also presented. The indent region was replicated and a scanning electron microscope (SEM) photograph of the indent replica is shown in Figure 10. In this illustration the grinding lines are obvious at the bottom of the indent and also the smearing over of the grinding lines surrounding the indent are obvious. The smearing of the grind lines is caused by metal-to-metal contact as the lubricating film is squeezed out.

Also, flaw printouts have been obtained on several new J57-#2 position bearings under radial flux orientation and investigations have shown an unusual radial flux signature characteristic associated with a grinding artifact. Selected results are presented in Figure 11. The optical surface photograph at 50X magnification shows what appears to be a region where the grinding wheel picked up metal from the surface and smeared it on the adjacent surface for a distance of approximately 0.015 in. Several photographs of a plastic replica from this region viewed through the SEM are presented in Figure 12. The low magnification view at the upper left shows the entire imperfection. The view at the upper right shows significantly increased detail and what appears to be metal removed and "scraped" along in the circumferential direction. Also, Region A is shown at high magnification in the lower left and it appears that a triangular shaped segment of the original metal surface remains with what may be cracks indicated by arrows. Evidence that this region is the original surface is provided by the grinding lines in this region. A magnified view of Region B is shown at the lower right where numerous small (approximately 2.54 μ or 0.0001 in. diameter) artifacts are observed. Also, near the lower center of Region B it appears that the grinding lines have been distorted.

B. Surface Flaws on Vendor Reprocessed Bearings

Magnetic perturbation, Barkhausen noise and laser scan records were acquired from a group of bearings in which the active race surfaces were reground (approximately 0.002 in. material was removed) by a vendor to determine the effectiveness of such a procedure for extending bearing life. New oversized rolling elements were used with the race components. Figure 13 shows magnetic perturbation records obtained on a reground inner race. The expanded horizontal axis record in the lower part of Figure 13 shows a well-shaped, symmetrical void polarity signal indicative of a pit, hole or nonmetallic inclusion, probably at or near the raceway surface. The region corresponding to the signature was examined under the microscope and the unusual appearance of the surface anomaly is shown in the upper photograph of Figure 14. The very regular, sharply defined and nearly perfect circular pattern on the compound, curved surface of this inner race generated intense interest. Furthermore, although the region appears to be relatively superficial and possibly only a blemish on the surface, the fact that a circumferential, high-flux density signal (CH) was obtained indicates that the anomaly or flaw has significant volume in which the magnetic permeability is lower than the surrounding metal matrix. This small diameter inner race was inserted in the chamber of a scanning electron microscope and several views obtained. A relatively low magnification view of the entire region is shown in the lower part of Figure 14. (The oval shape of the boundary region is caused by the angle of viewing). It is apparent that the well-defined circular outline still exists; accordingly, this line is not just a stain, but is a true topographical feature. Additional views of regions A and B are shown at higher magnifications in Figure 15 along with an X-ray fluorescence scan for oxygen in region B. In region B additional cracks are evident and the X-ray image obtained during a scan for oxygen indicates that this region contains significant oxides. It was the opinion of the metallurgist that the overall evidence indicates rust penetrating into the surface of the bearing race.

During routine inspection on the CIBLE equipment of 20 J57-#2 bearings (3 components per bearing, i.e., two inner race halves and one outer race) reprocessed by a vendor after engine service, computer printouts were obtained on 4 components. All areas were investigated at the signature locations and in each instance correlation with a visual surface anomaly was obtained. Information from the most prominent example is presented in Figure 16. The computer printout is at the upper left and the circumferential high-field signature (CH) and radial high-field signatures (RH) associated with the flaw on Track 0004 and at the azimuthal location 4851 along with a surface photograph of the flaw are presented. (The

difference of seven counts between the circumferential signature indicated locations is not significant.) The fact that the circumferential signature is not symmetrical about the zero crossing is probably caused by the unsymmetrical flux perturbation generated by the two separate anomalies in the flaw region, but could also be caused by subsurface features not disclosed by the surface photograph. A plastic replica was made of this flaw region and several SEM views of the replica are presented in Figure 17. Note the loss of material and rather extensive cracking in the two upper photographs. Also, note in the lower region of the flaw that a metal chip, approximately 0.003 in. long measured across (vertical) the race surface appears to have continuous surface cracks and is probably near the point of breaking away from the surface. The magnified view of region A shown in the lower left photograph clearly shows that there is an opening from the surface to a significant depth as shown in the upper part of this photograph.

C. Residual Stresses

Several examples of Barkhausen residual stress signatures will be presented in this section. Results obtained on inner races of J85-#2 main shaft bearings before and after actual routine engine service have shown very interesting results. A typical set of data are presented in Figure 18. The two upper analog signatures were obtained at the gaging contact angle of 28.5° (this is near the center of the heaviest stressed region of the ball track during service) and at a similar location on the nonloaded half of the inner bearing races. After 986 hours' service, the signatures in the two lower photographs were obtained. On the nonloaded half, note that the signatures are practically identical before and after service. By contrast, near the leading edge of the analog signature on the loaded half, a pronounced spike is now observed. This spike signature is interpreted as being a service induced decrease of the beneficial residual compression stresses which existed in the bearing after manufacture. Other information (26) reports an investigation which shows that the heavy load stresses cause a subsurface material transformation and an associated volume expansion of the transformed region. This increased volume creates a subsurface tension region located at a depth of approximately 0.005 in. It is reasonable to assume that the Barkhausen signature spike is caused by such a tension region on the J85 bearing of Figure 18. Additional investigations are planned to confirm this possibility.

Barkhausen signatures on new bearings (J57-#2 position inner races) are presented in Figure 19. Signatures on most of the bearings of this type were typical of those shown in the two records at the left and indicate compression stresses. By contrast, the small spike on the signature at the upper right and the large spike on the signature at the lower right are characteristic features indicative of undesirable conditions of residual stress in a new bearing.

D. Subsurface Flaws - New Premium Quality Bearings

Although the use of premium quality consumable electrode vacuum arc remelt materials minimize the occurence of inclusions, in premium quality bearings, occasionally an inclusion is encountered even in bearings fabricated from such materials. An example of signatures indicating subsurface inclusions in a J85-#2 position inner bearing race is presented in Figure 20. Each record is the magnetic perturbation circumferential flux signature obtained with one complete revolution of the bearing race. The upper record in each set of two records was obtained before engine service and the lower record, after 945 hours engine service. Starting at the upper record, a prominent void polarity signature "B" (well above the surrounding background magnetic signatures) is observed. After the probe is indexed to the next adjacent scan track, a second signature marked "A" is also observed, and as the probe is moved to the next scan track, signature "A" is observed and "B" is no longer obtained. Analyses of these results and other data indicate that two separate subsurface inclusions, each at least 0.002 in. in diameter and located approximately 0.003 in. beneath the surface, exist in this new, high-quality bearing. The records obtained after service indicate essentially no changes and this should be anticipated since these records were all obtained on the nonloaded half of the split inner race. Based on the results of extensive endurance testing in the laboratory in which such signatures almost invariably are the initiation source of spalling type failures, it is suggested that if these signature regions had been located in the load-track region of the bearing, this bearing would have failed in actual engine service. Further data supporting this suggestion are presented in the next paragraph.

During a screening inspection on a group of J57-#4 position bearing inner races that had been categorized "reparable rejects" and in which the Air Force "green tag" had indicated rust pits, several magnetic perturbation printouts were obtained on the CIBLE equipment. The printout obtained on bearing S/N 493-1 is shown in Figure 21. Note that a single circumferential high-flux density (CH) signature is obtained in the load track region (probe step 0007) at an angular location of 4950 counts from the reference zero mark on the bearing race. No radial flux signature is obtained; accordingly, this is evidence that the signature is from a subsurface source. Although several laser (LA) printouts were obtained on this used bearing possibly from some of the rust pits, no laser signature is coincident with the magnetic perturbation signature; this is additional evidence that the signature source is subsurface. Also, actual recordings (at two different horizontal axis expansions) of the signature are shown in Figure 21. Such a well-defined symmetrical signature is characteristic of those associated with subsurface inclusions; analysis of the peak-to-peak separation indicates the centroid of the inclusion to be approximately 0.0025 to 0.003 in. beneath the surface, and the amplitude indicates that the diameter of the inclusion is approximately 0.002 in.

Since this inclusion signature occurs in the load zone of this bearing, it was selected for endurance testing in the laboratory. Accordingly, the bearing was assembled and installed in the endurance testing rig. After only 16 hours running time, the vibration sensor on the rig caused automatic shut-down

of the system. The operator restarted the machine and after a short time, automatic shut-down occurred again. The bearing was removed from the rig and examination of the disassembled bearing indicated a massive spall on the inner race as shown in Figure 22. A cursory examination disclosed that the spall was located near the zero reference mark on the bearing race and since this was only 150 counts from the inclusion signature at 4850 counts, it appeared that the inclusion probably caused initiation of the spall. Subsequently, a comprehensive correlation investigation confirmed that the inclusion was located in the extreme leading edge of the spall and this is conclusive evidence that the inclusion initiated the failure. Results of the correlation are shown in Figure 23. The width of scan track 0007 is shown and also the precise location of 4850 counts has been added to the photograph. Note that this location coincides exactly with the black region indicated by the arrows and which initiated the spall. Other arrows indicate cracking in this region of the spall. Although this bearing previously had received approximately 6600 hours actual engine service, the bearing had not failed; however, it is suggested that this extended service had already caused a network of subsurface cracks which may have "primed" the bearing for failure. Furthermore, it is reasonable to assume that if this bearing had not been inspected using the CIBLE equipment, it would have been reworked and subsequently installed in an engine (since the green tag indicated only rust pits and many bearings in such a category are returned to service after a nominal rework in which the rust is removed). Had this been the case, undoubtedly a bearing engine failure would have occurred after a few hours of engine operation. It is also important to emphasize that during the endurance tests the bearing did not fail from any of the indicated anomalies, rust pits, which had placed the bearing in the green tag category, but had failed from a flaw that was missed by all of the prior inspections conducted from the time the bearing was manufactured.

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NON-DESTRUCTIVE INSPECTION AND RELATIONSHIPS TO AIRCRAFT DESIGN--ETC(U)
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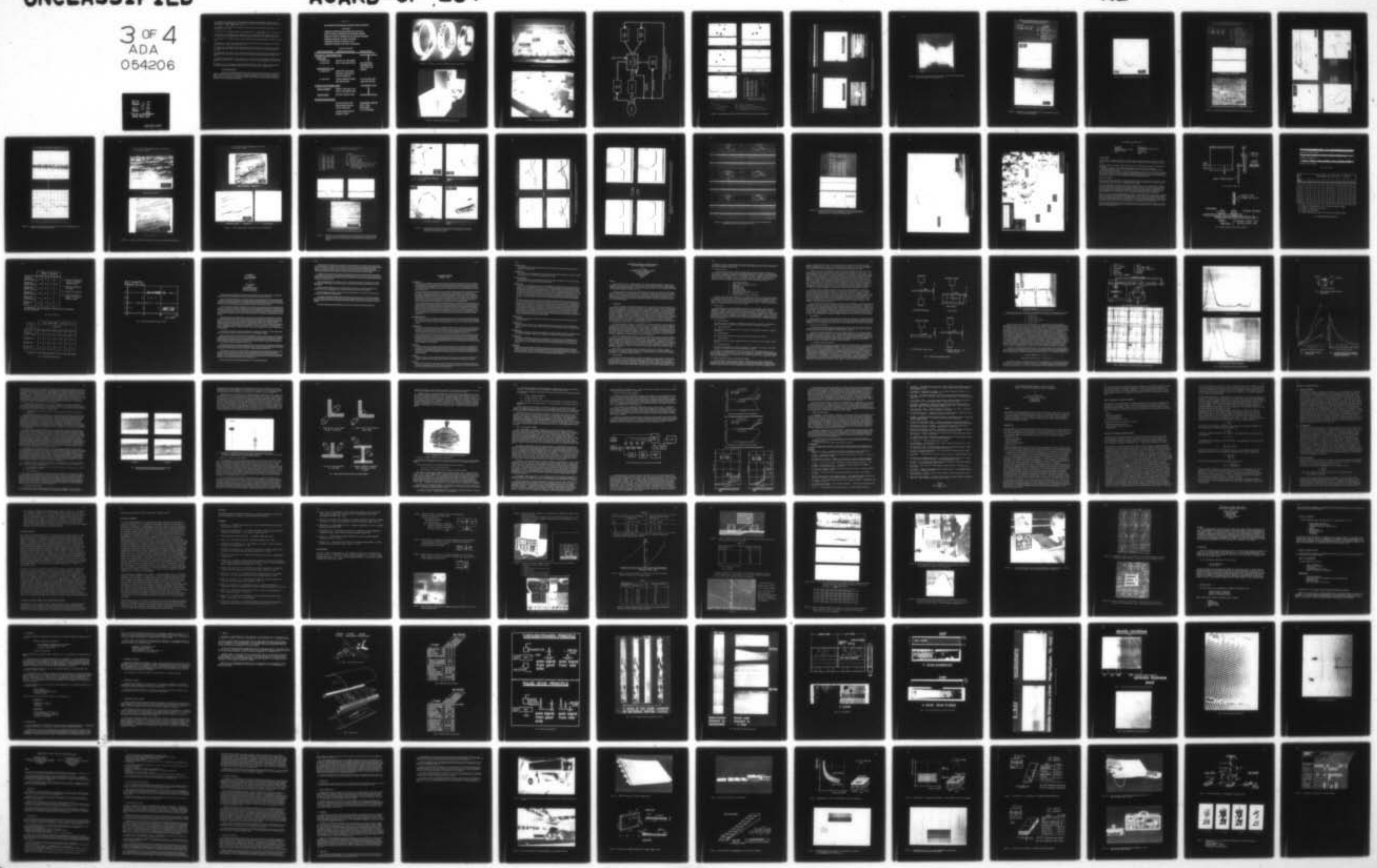

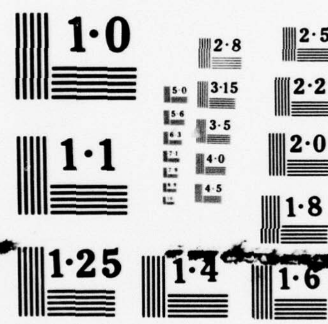

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MICROCOPY RESOLUTION TEST CHART

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ACKNOWLEDGEMENTS

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TABLE I.

AUTOMATED BEARING INSPECTION SYSTEM

FEATURES

COMPUTER SUPERVISED AND CONTROLLED INSPECTION
RAPID FIXTURING CHANGEOVER FOR DIFFERENT BEARINGS
COMPUTER SETUP OF PARAMETERS FOR DIFFERENT BEARINGS
COMPUTER PRINTOUT OF SIGNAL LOCATIONS
PERMANENT RECORD ON MAGNETIC TAPE
DIAGNOSTIC PRINTOUTS AND SAFETY INTERLOCKS

SPECIFICATIONS

INSPECTION METHODS	CONDITIONS DETECTABLE	SCAN PATTERN
MAGNETIC PERTURBATION		
RADIAL FLUX		
• HIGH FIELD	SURFACE PITS, INCLUSIONS,	
• LOW FIELD	SPALLS AND INDENTATIONS	0.025-INCH WIDE CIRCUMFERENTIAL STRIPS WITH 20% OVERLAP
CIRCUMFERENTIAL FLUX		
• HIGH FIELD	SUBSURFACE INCLUSIONS, AND SPALLS AND DEEPER SURFACE ANOMALIES	
• LOW FIELD	FATIGUE DAMAGED REGIONS AND INDENTATIONS	12 TO 60 SCANS PER INSPECTION METHOD
LASER-SCATTERED LIGHT		SYNCHRONIZED SCANS
SURFACE ANOMALY	SURFACE SCRATCHES, PITS, SPALLS, AND INDENTATIONS	
SURFACE FINISH	RELATIVE SURFACE FINISH	
BARKHAUSEN NOISE		
	RELATIVE SURFACE AND NEAR-SURFACE RESIDUAL STRESS CONDITIONS	PROGRAMMED SAMPLING 0.050×0.050-INCH REGIONS 9 TO 15 LOCATIONS
	SERVICE MODIFICATION OF RESIDUAL STRESS	

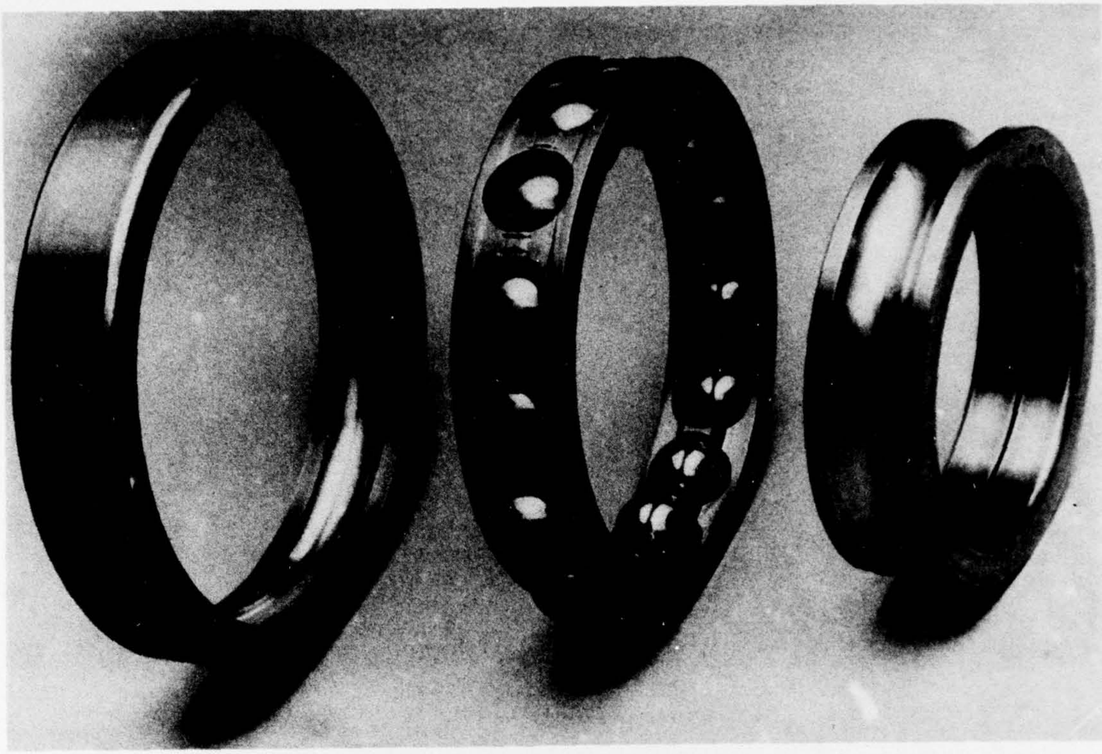


FIGURE 1. PRECISION ROLLING ELEMENT BEARING COMPONENTS

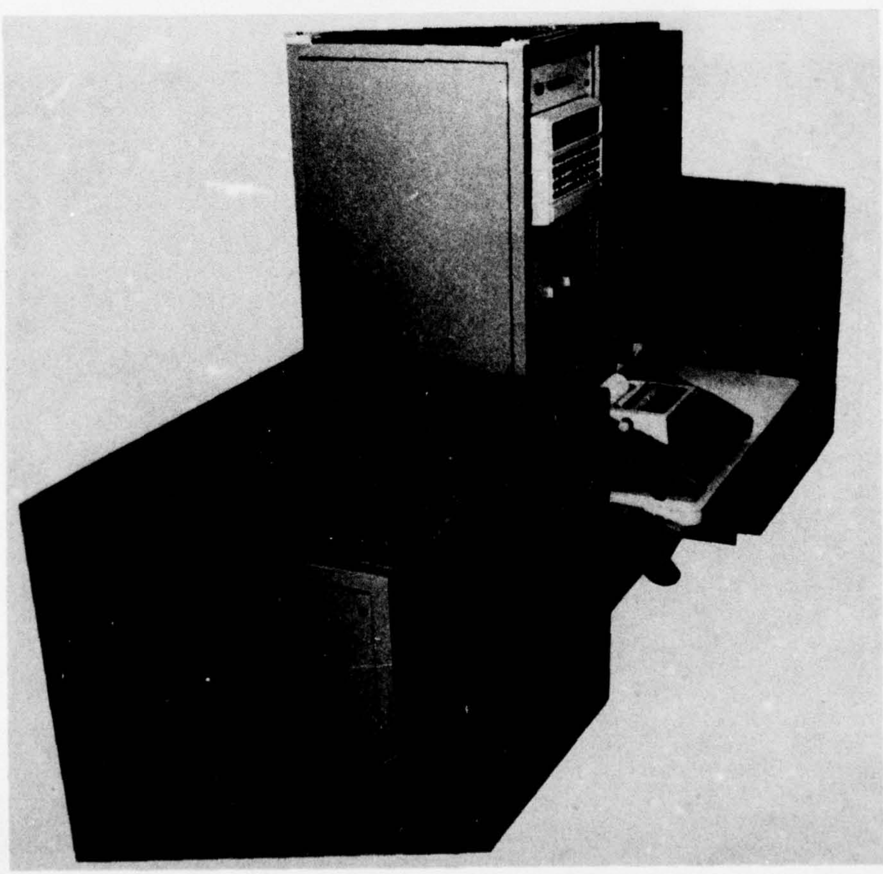


FIGURE 2. CIBLE BEARING INSPECTION SYSTEM

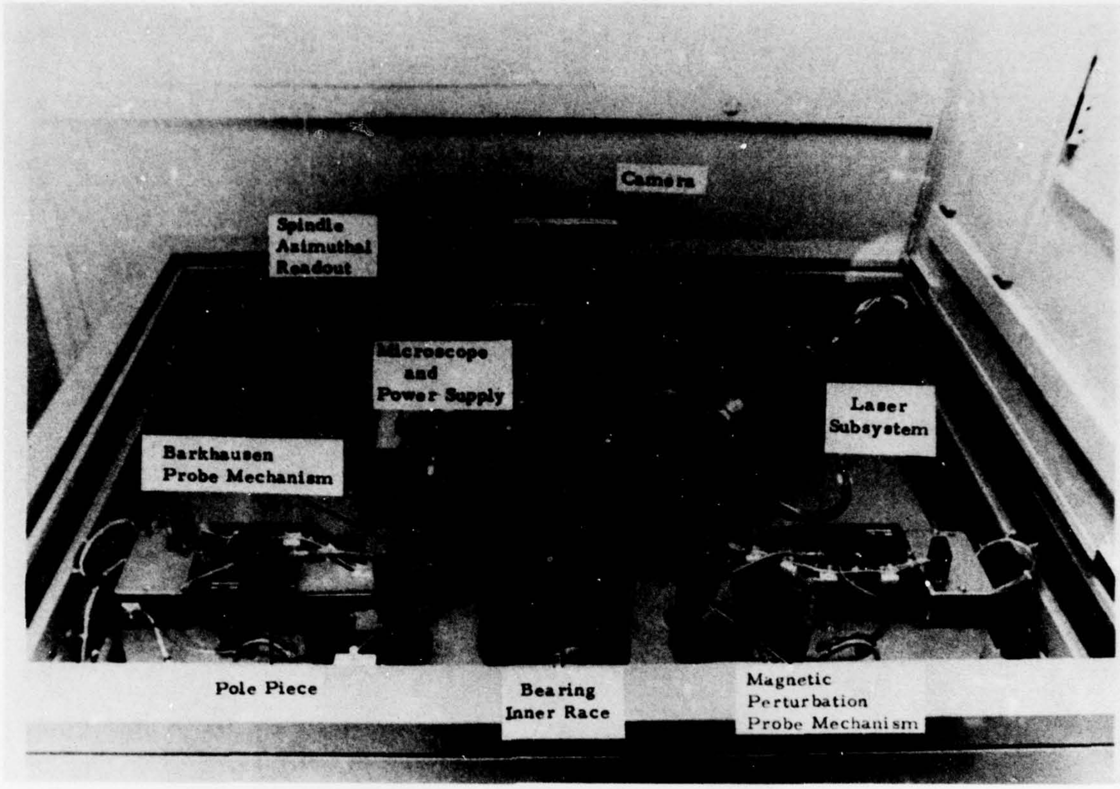


FIGURE 3. RACE INSPECTION UNIT

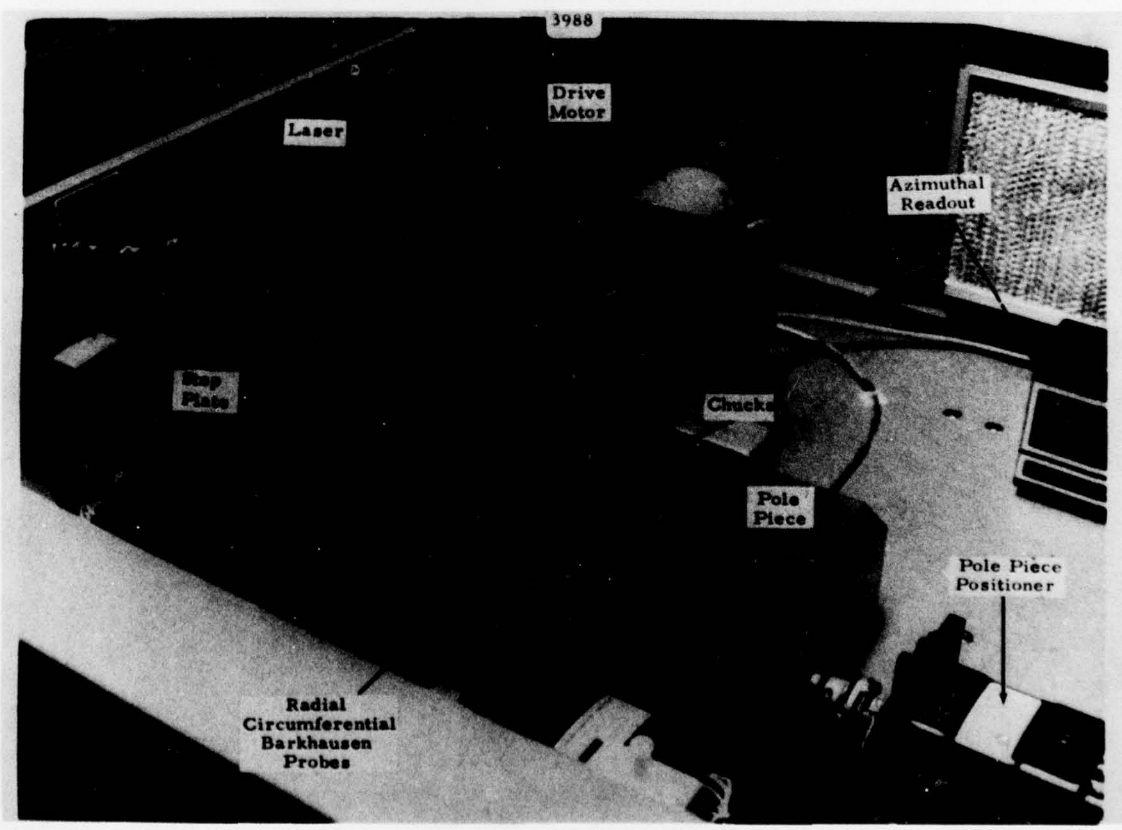


FIGURE 4. BALL/ROLLER INSPECTION UNIT

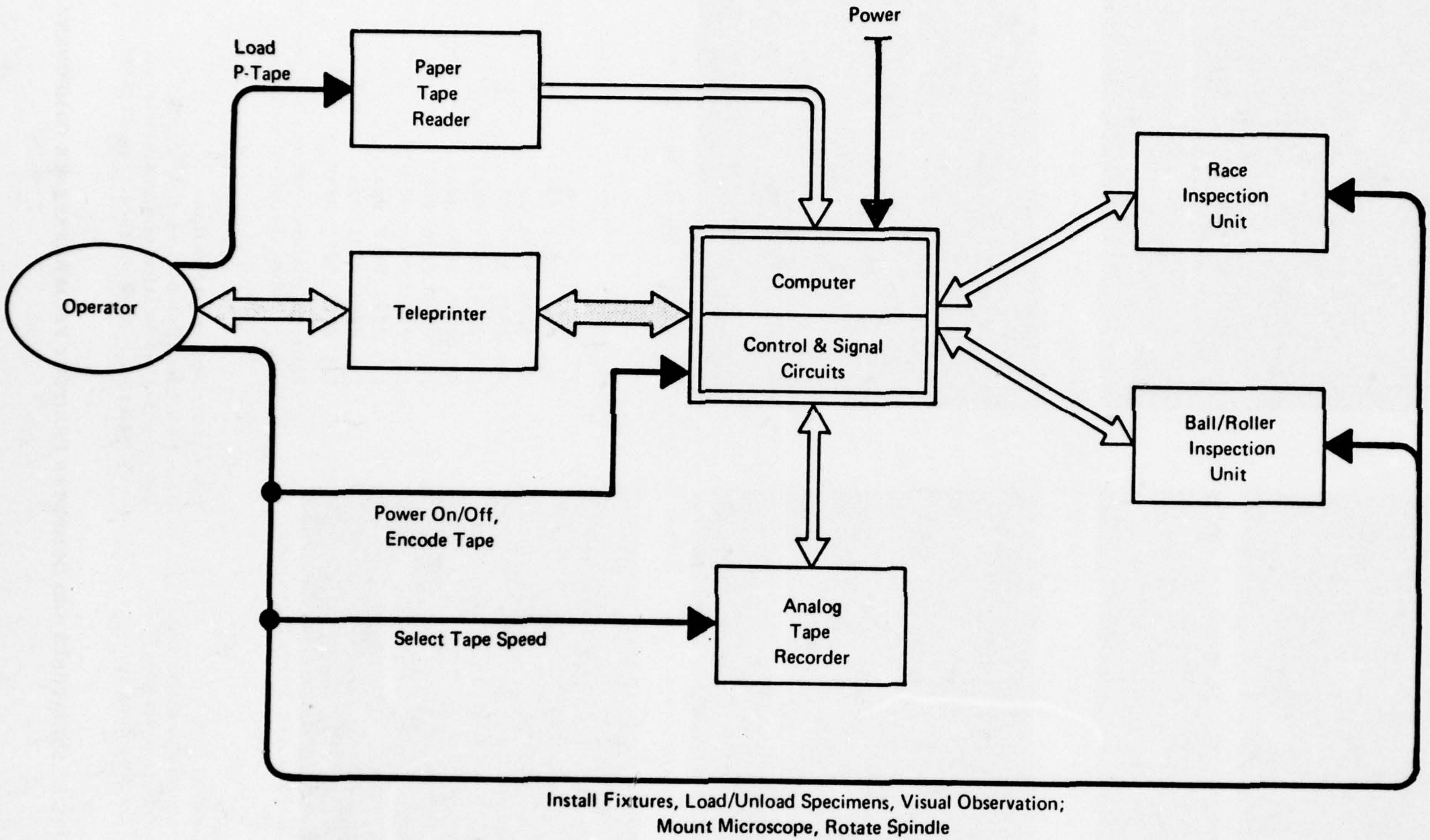
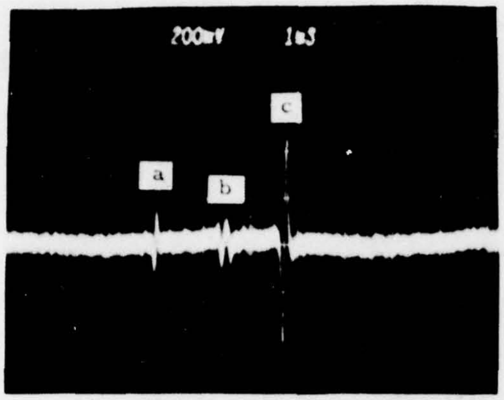
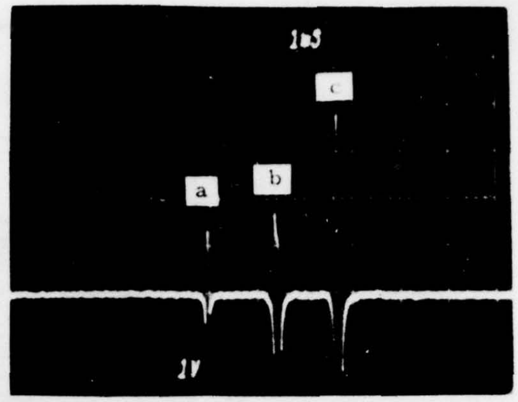
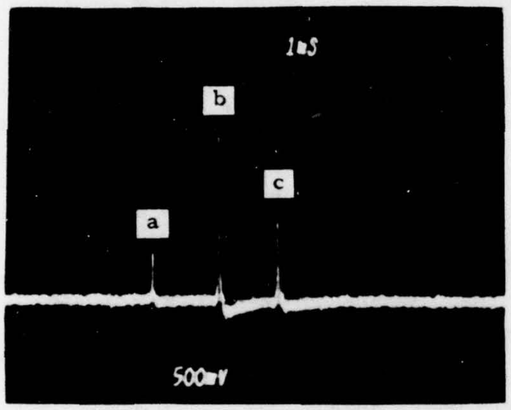


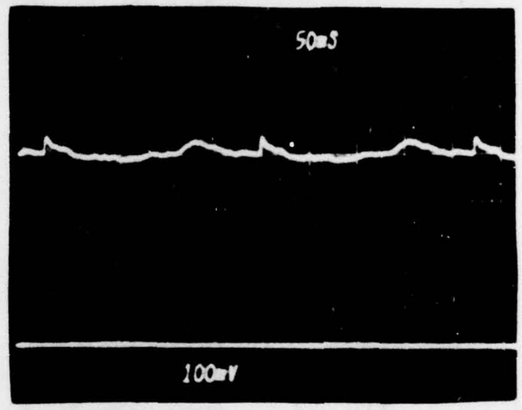
FIGURE 5. SYSTEM DIAGRAM



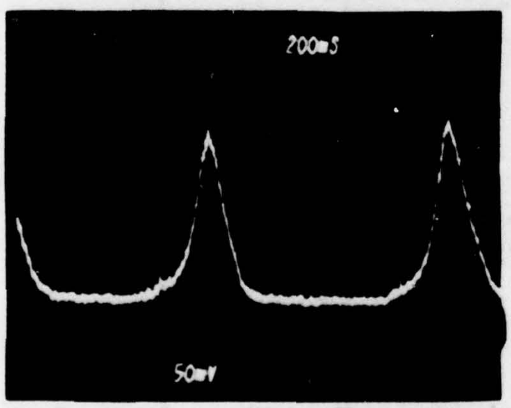


A - CH Signatures Magnetic Perturbation B - RH Signatures





C - LA Signatures Laser Scattered Light D - LD (Surface Finish)



E - Barkhausen Noise Signature

FLAWS

TY	S T	B R	S R	Signature	
RH	ØØØ5	ØØØ1	ØØ24	a	B
RH	ØØØ5	ØØ32	ØØ55	b	B
RH	ØØØ5	ØØ59	ØØ82	c	B
CH	ØØØ5	ØØ6Ø	ØØ83	c	A
RL	ØØØ5	ØØØ1	ØØ24		
RL	ØØØ5	ØØ32	ØØ55		
RL	ØØØ5	ØØ6Ø	ØØ83		
CL	ØØØ5	ØØ6Ø	ØØ83		
LA	ØØØ5	ØØ31	ØØ54	b	C
LA	ØØØ5	ØØ59	ØØ82	c	C

Note: Signatures not printed are below threshold settings.

Legend:

- R - radial flux
- C - circumferential flux
- H - high flux density
- L - low flux density
- LA - laser, pit imperfection
- ST - probe location across race groove
- BR - azimuthal location of signature from reference mark on race (1 rev = 5000)

FIGURE 6. SIGNATURES AND COMPUTER PRINTOUT FROM REFERENCE COMPONENT

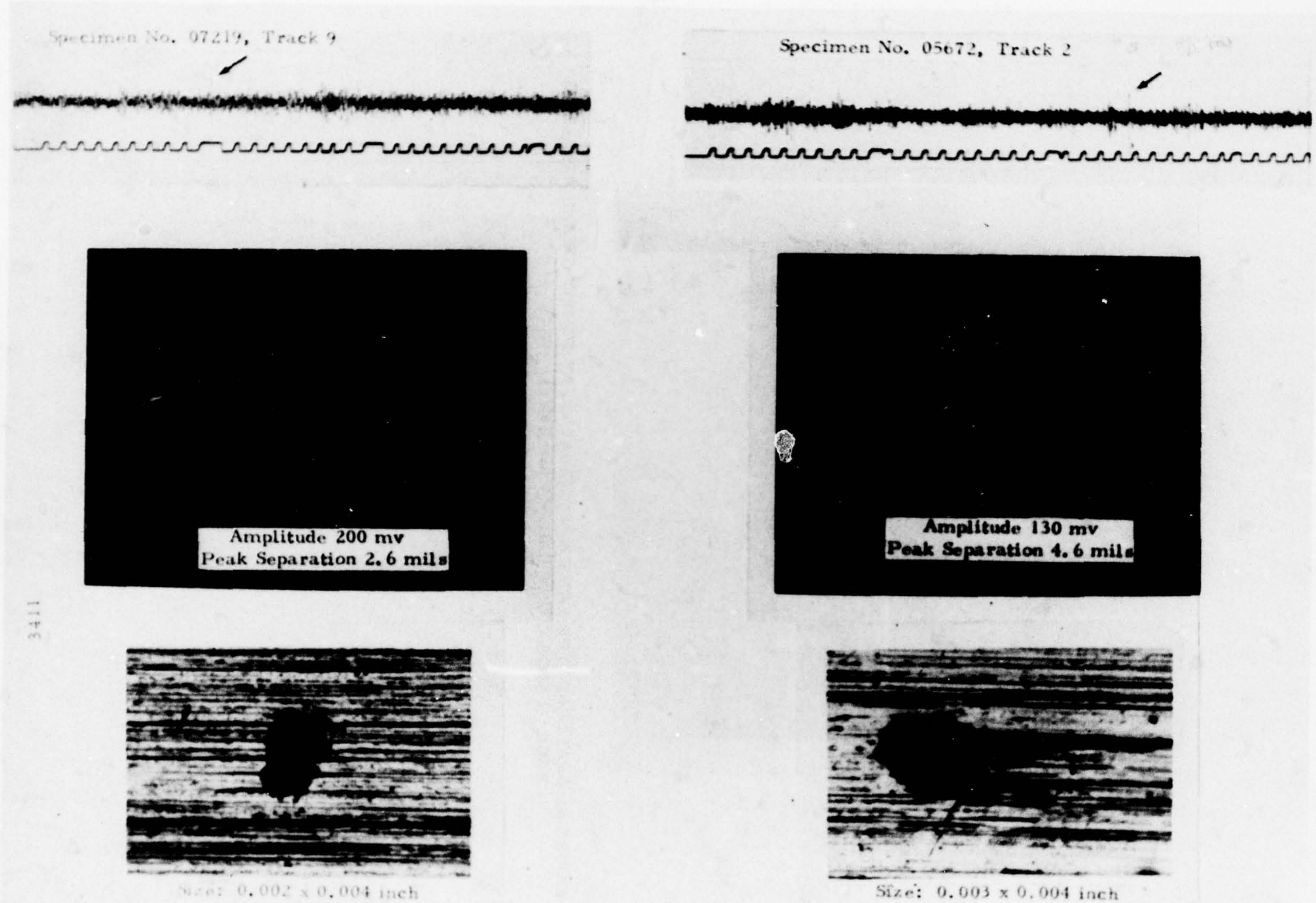


FIGURE 7. CORRELATION OF MAGNETIC PERTURBATION SIGNATURES AND SURFACE FLAWS ON NEW J85-#2 BEARING INNER RACES

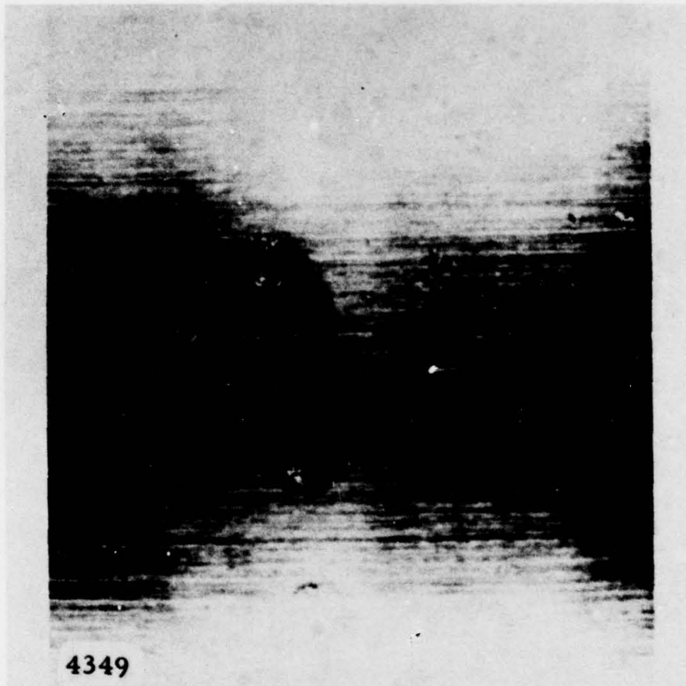


FIGURE 8. SPALLING TYPE FAILURE ORIGINATING AT INDENT ON INNER BEARING RACE (LABORATORY ENDURANCE TEST)

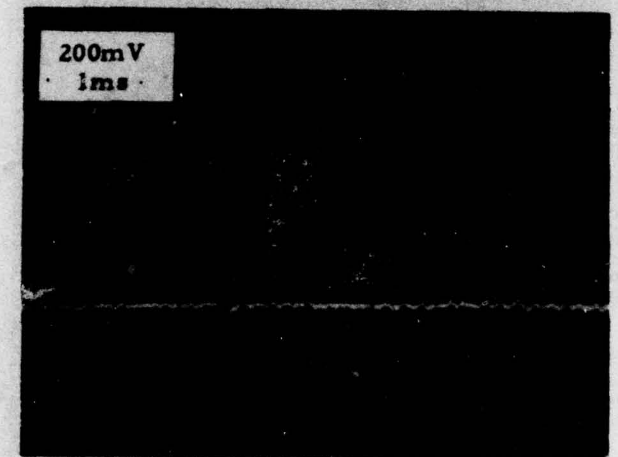
Flaw Printout Obtained During Automatic Magnetic Perturbation Inspection

FLAWS

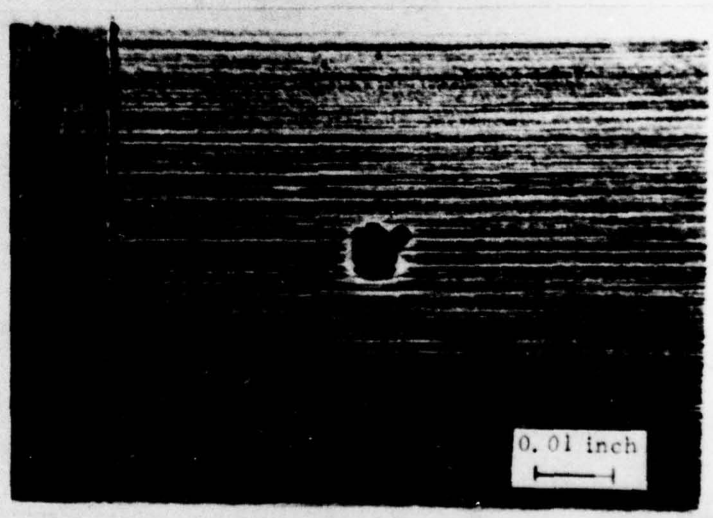
TY	ST	BR	SR
RH	0007	2792	2792

LEGEND

R - radial flux
H - high flux density
ST - probe location across race groove
BR - azimuthal location of signature from reference mark on race
(1 Rev = 5000)



RH Signature @ 0007 - 2792



Magnified (50X) View of Surface @ 0007 - 2792

FIGURE 9. SIGNATURE (RH) FROM INDENT ON J57-#4 BEARING (S/N 557V-1) OUTER RACE (NEW BEARING)

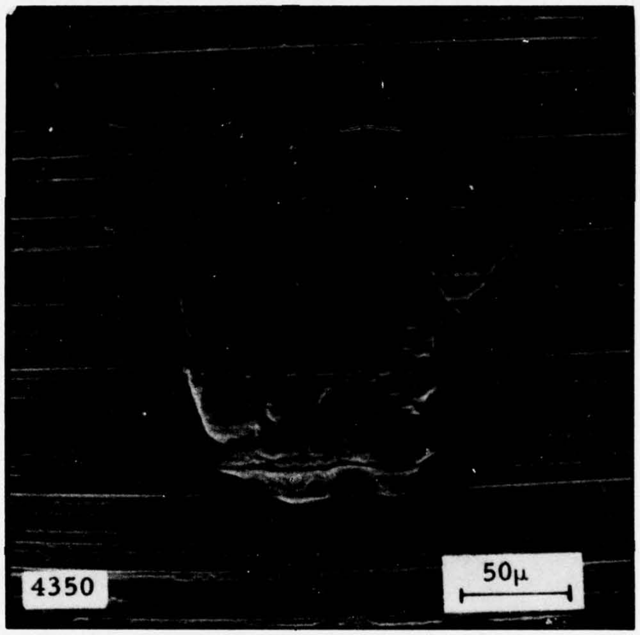


FIGURE 10. SEM PHOTOGRAPH OF INDENT REPLICA

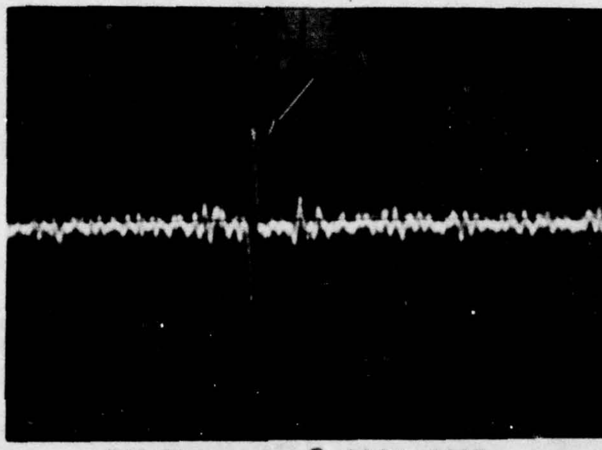
Flaw Printout Obtained During Automatic
Magnetic Perturbation Inspection

FLAWS

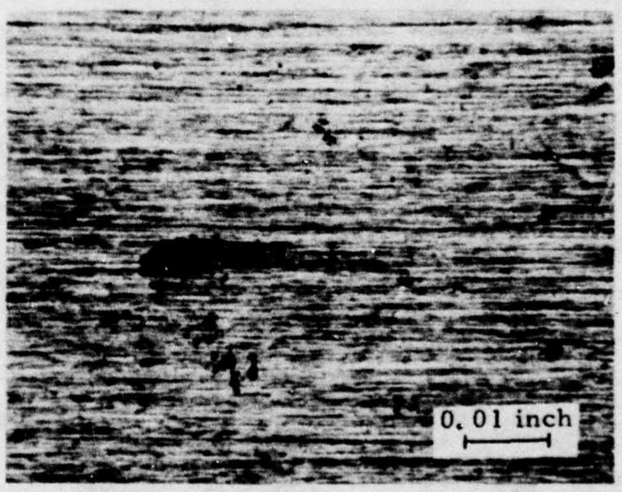
TY	S T	B R	S R
RH	ØØØ5	44Ø5	4427
RL	ØØØ5	44Ø5	4427

LEGEND

R - radial flux
H - high flux density
L - low flux density
ST - probe location across race groove
BR - azimuthal location of signature from reference mark on race (1 rev = 5000)



RH Signature @ 0005-4405



Magnified (50X) View of Surface @ 0005-4405

FIGURE 11. SIGNATURE FROM GRINDING ARTIFACT ON NEW BEARING

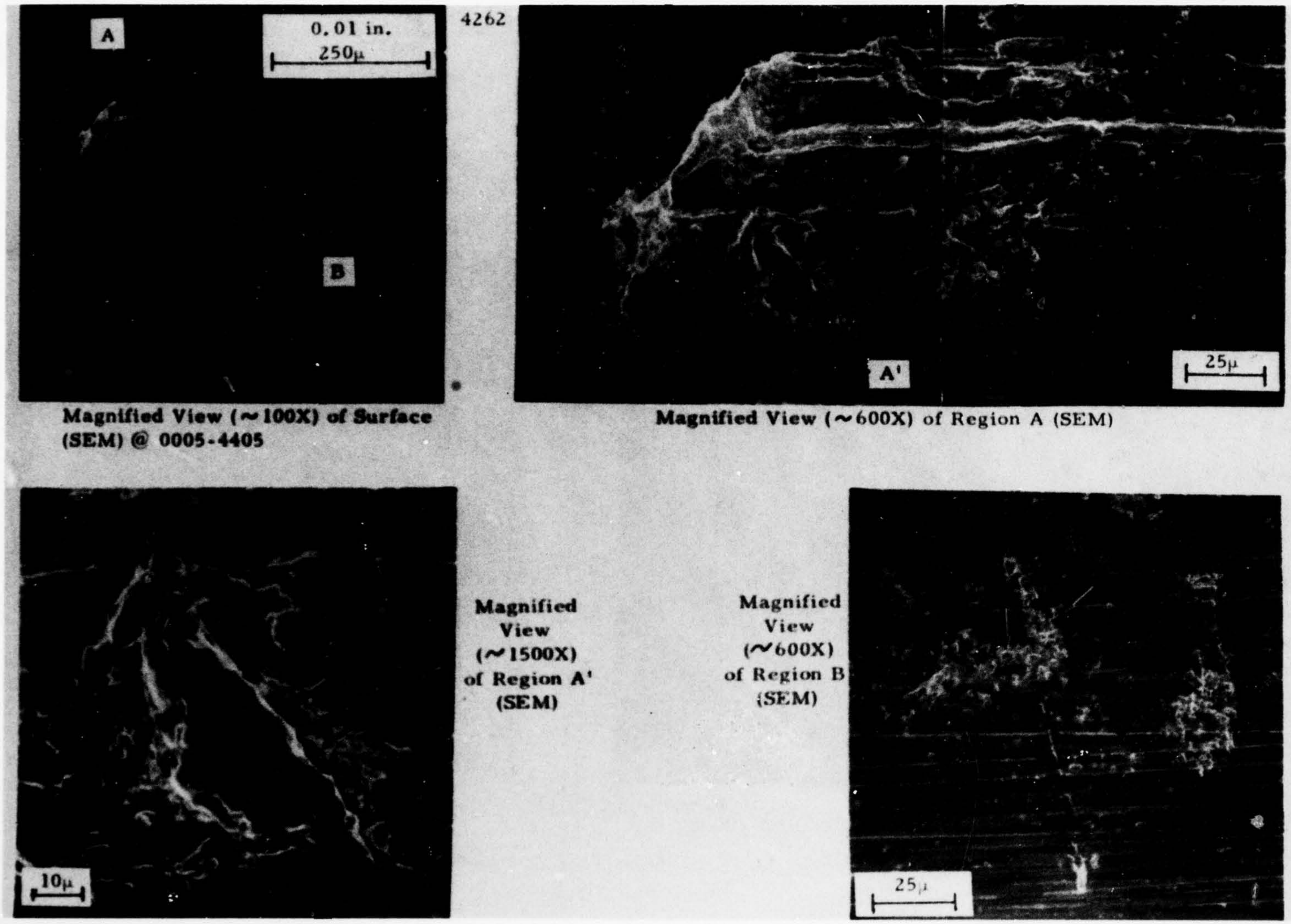


FIGURE 12. SCANNING ELECTRON MICROSCOPE (SEM) PHOTOGRAPHS OF SURFACE IMPERFECTION (REPLICA) AT 0005-4405, J57-#2 BEARING (S/N 704A-1) INNER RACE (NEW BEARING)

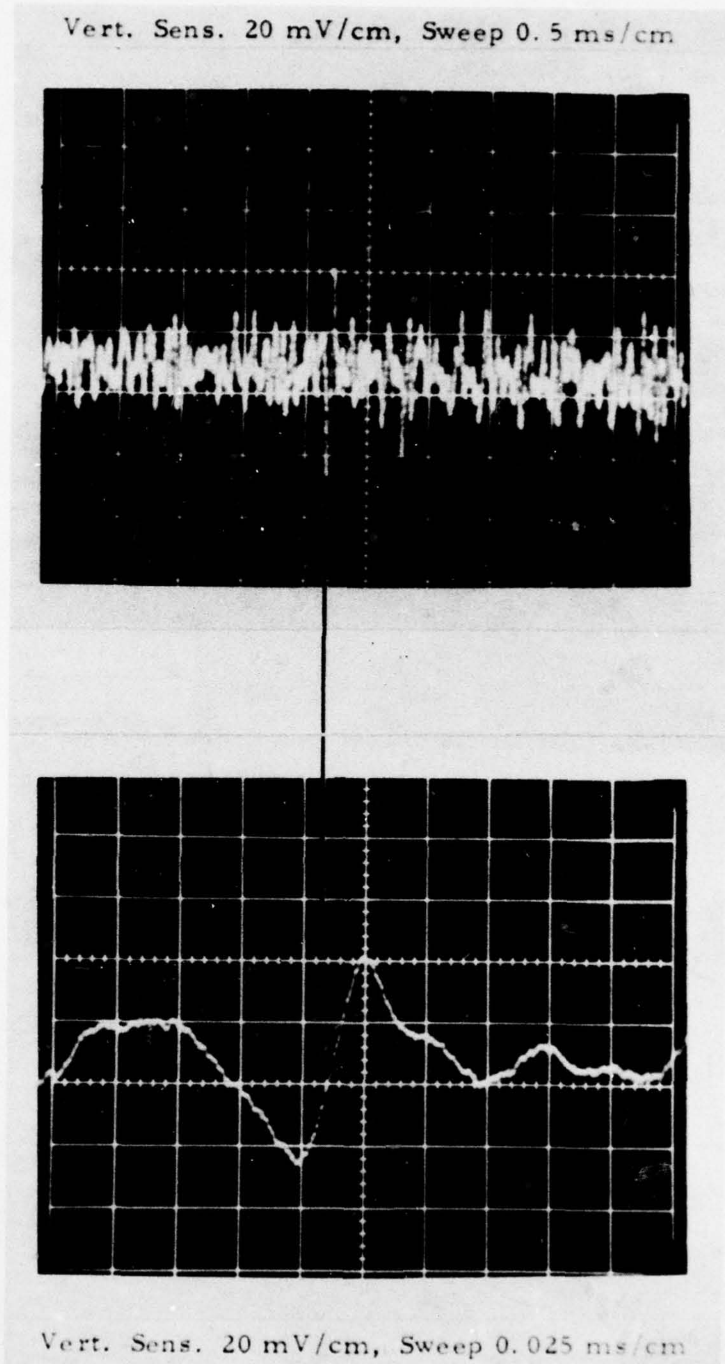
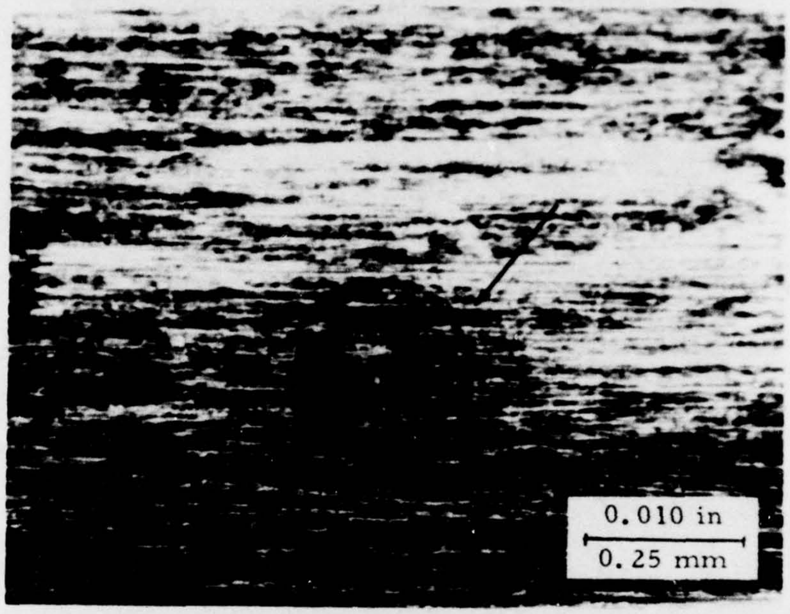
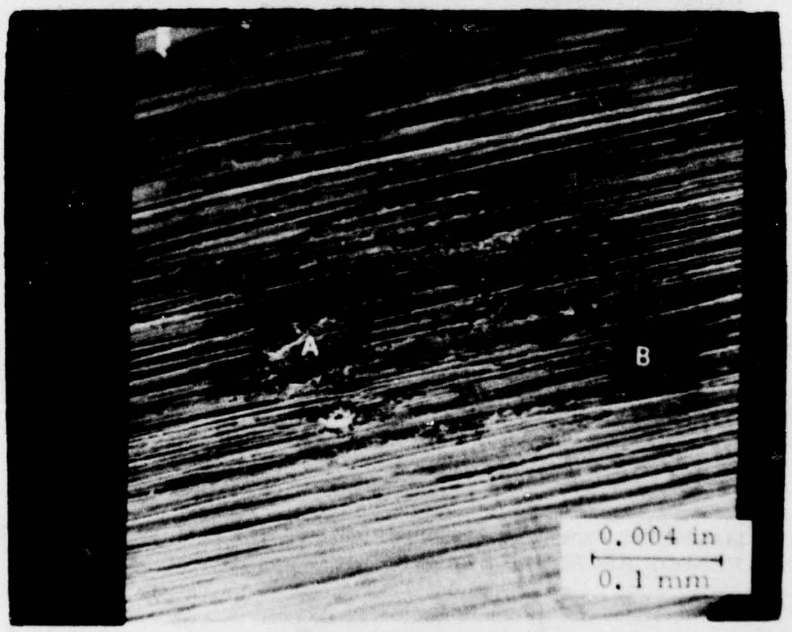


FIGURE 13. MAGNETIC PERTURBATION (CIRCUMFERENTIAL FLUX) SIGNATURE FROM VENDOR REGROUND BEARING RACE

P/N 1-300-015 Inner Bearing Race, Reworked
S/N 28, Side 2 (344°)



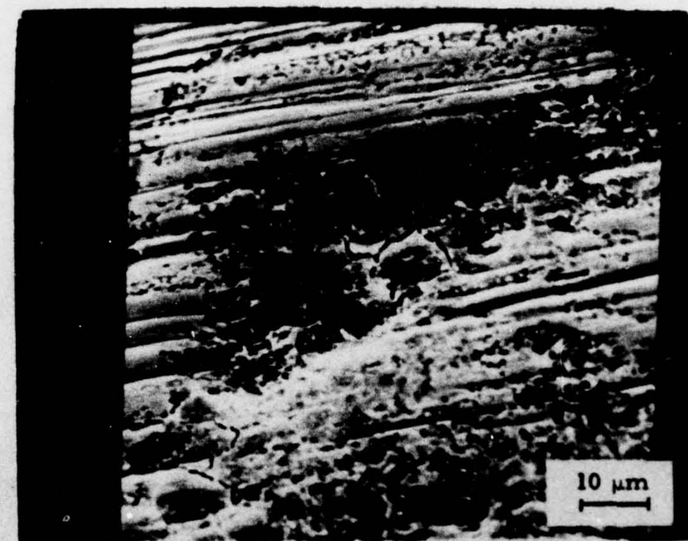
Optical Micrograph



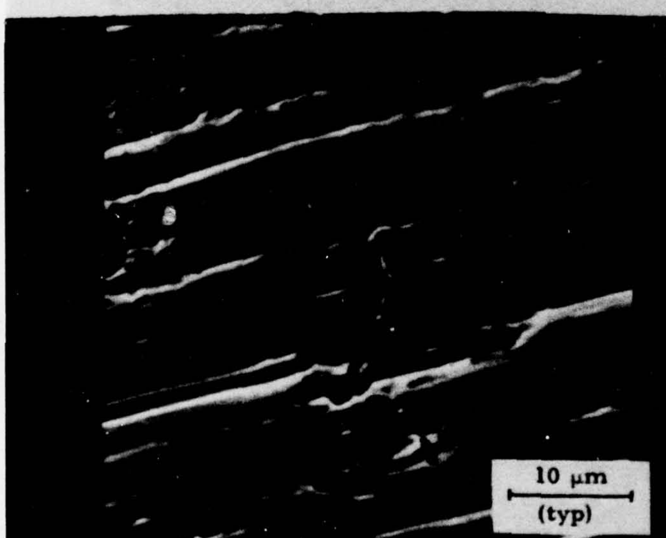
SEM Micrograph

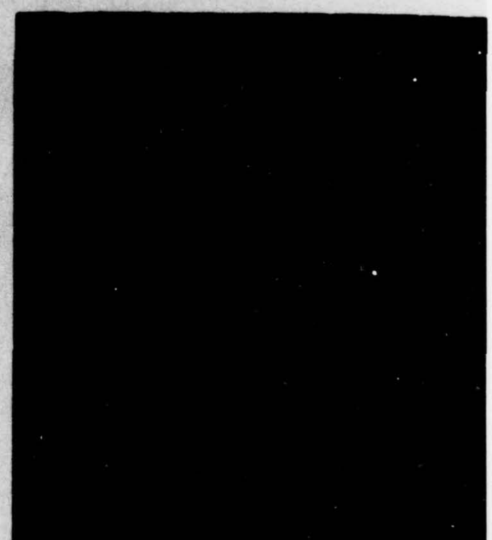
FIGURE 14. OPTICAL AND SEM PHOTOGRAPHS OF FLAW IN REGROUND BEARING RACE

P/N 1-300-015, Inner Bearing Race, Reworked
S/N 28, Side 2 (344°)



SEM Micrograph Region A





SEM Micrograph Region B X-Ray Image

FIGURE 15. SEM VIEWS SHOWING CRACKS AND X-RAY FLUORESCENCE

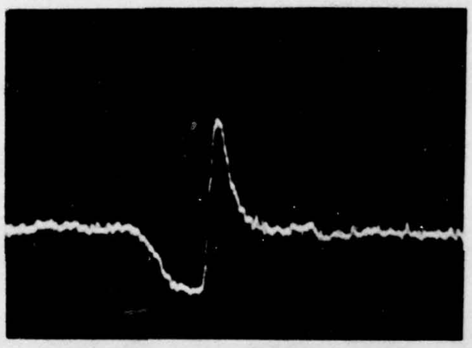
Flaw Printout Obtained During Automatic
Magnetic Perturbation Inspection

FLAWS

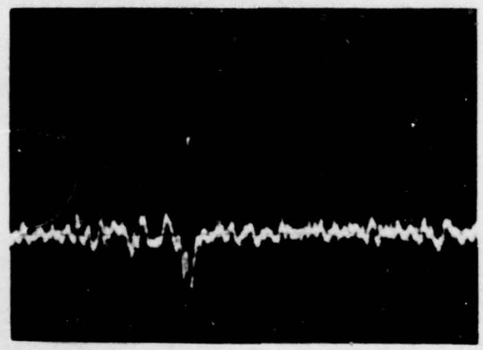
TY	ST	BR	SR
RH	ØØØ4	4858	4871
CH	ØØØ4	4851	4864
RH	ØØØ5	444Ø	4453
CH	ØØØ5	4851	4864
RL	ØØØ4	4858	4871
RL	ØØØ5	444Ø	4453
CL	ØØØ5	4851	4864

END MP.

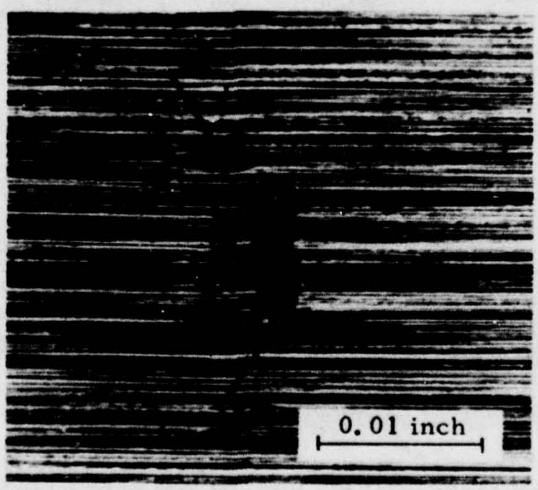
Legend:
- C - circumferential flux
- R - radial flux
- H - high flux density
- L - low flux density
- ST - probe location across race groove
- BR - azimuthal location of signature from reference mark on race (1 rev = 5000)



CH Signature @ 0004-4851

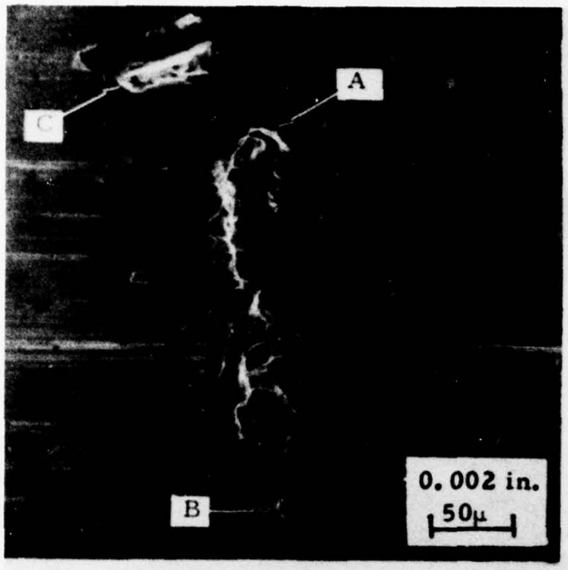


RH Signature @ 0004-4858



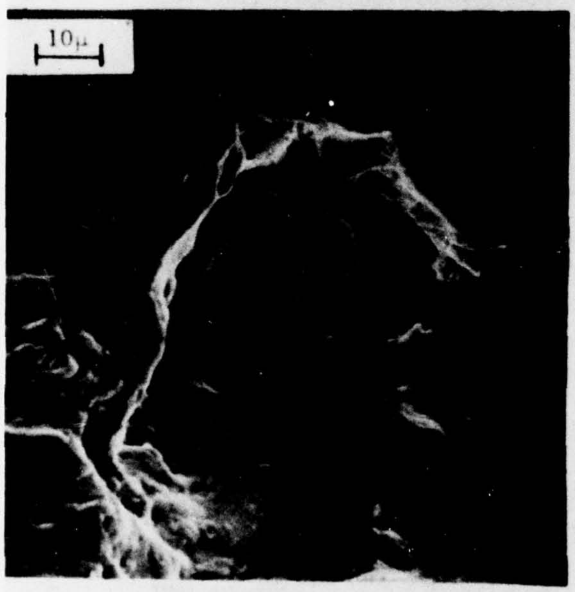
Magnified (100X) View of Surface Showing the Flaw that Caused the CH and RH Signatures

FIGURE 16. COMPUTER PRINTOUT MAGNETIC PERTURBATION SIGNATURES (CH AND RH), AND FLAW IN J57-#2 BEARING (S/N B 1274-2) OBTAINED ON VENDOR REPROCESSED BEARING (AFTER PROCESSING, BEARING IS "ZERO" TIMED BY AIR FORCE).



Magnified View (~250X) of Surface (SEM) @ 0004-4851

Magnified View (~1500X) of Region B (SEM)



Magnified View (~1500X) of Region A (SEM)

Magnified View (~600X) of Region C (SEM)

FIGURE 17. SCANNING ELECTRON MICROSCOPE (SEM) PHOTOGRAPHS OF SURFACE IMPERFECTION (REPLICA) AT 0004-4851, J57-#2 BEARING (S/N B1274-2) INNER RACE (REWORKED BEARING)

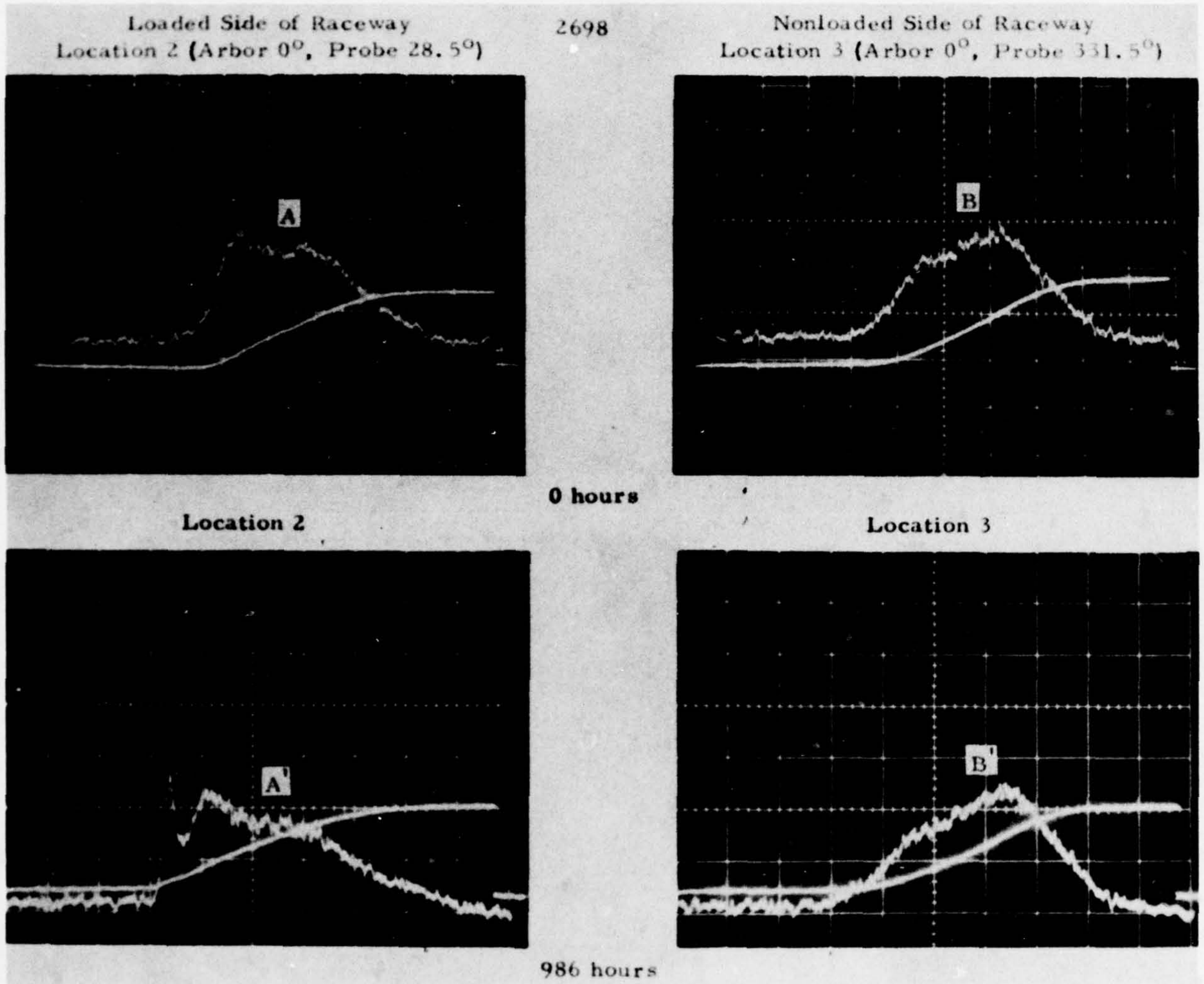


FIGURE 18. TYPICAL BARKHAUSEN SIGNATURES BEFORE AND AFTER APPROXIMATELY 1000 HOURS SERVICE ON A J85 MAIN SHAFT BEARING (S/N 07257)

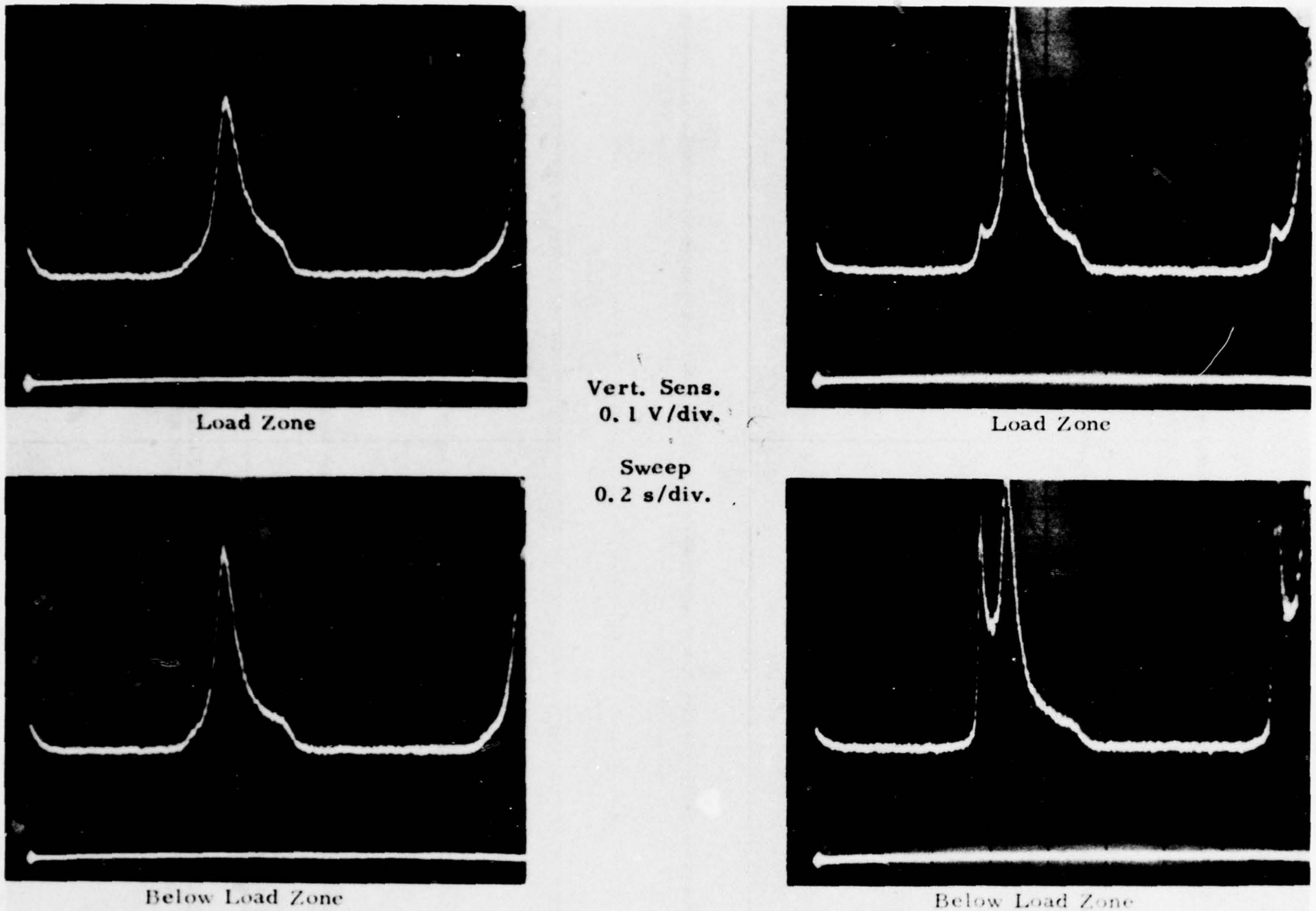


FIGURE 19. TYPICAL BARKHAUSEN DATA ON NEW BEARINGS WITH UNIFORM COMPRESSION STRESS (LEFT COLUMN) AND NONUNIFORM TENSION STRESS (RIGHT COLUMN) SIGNATURES

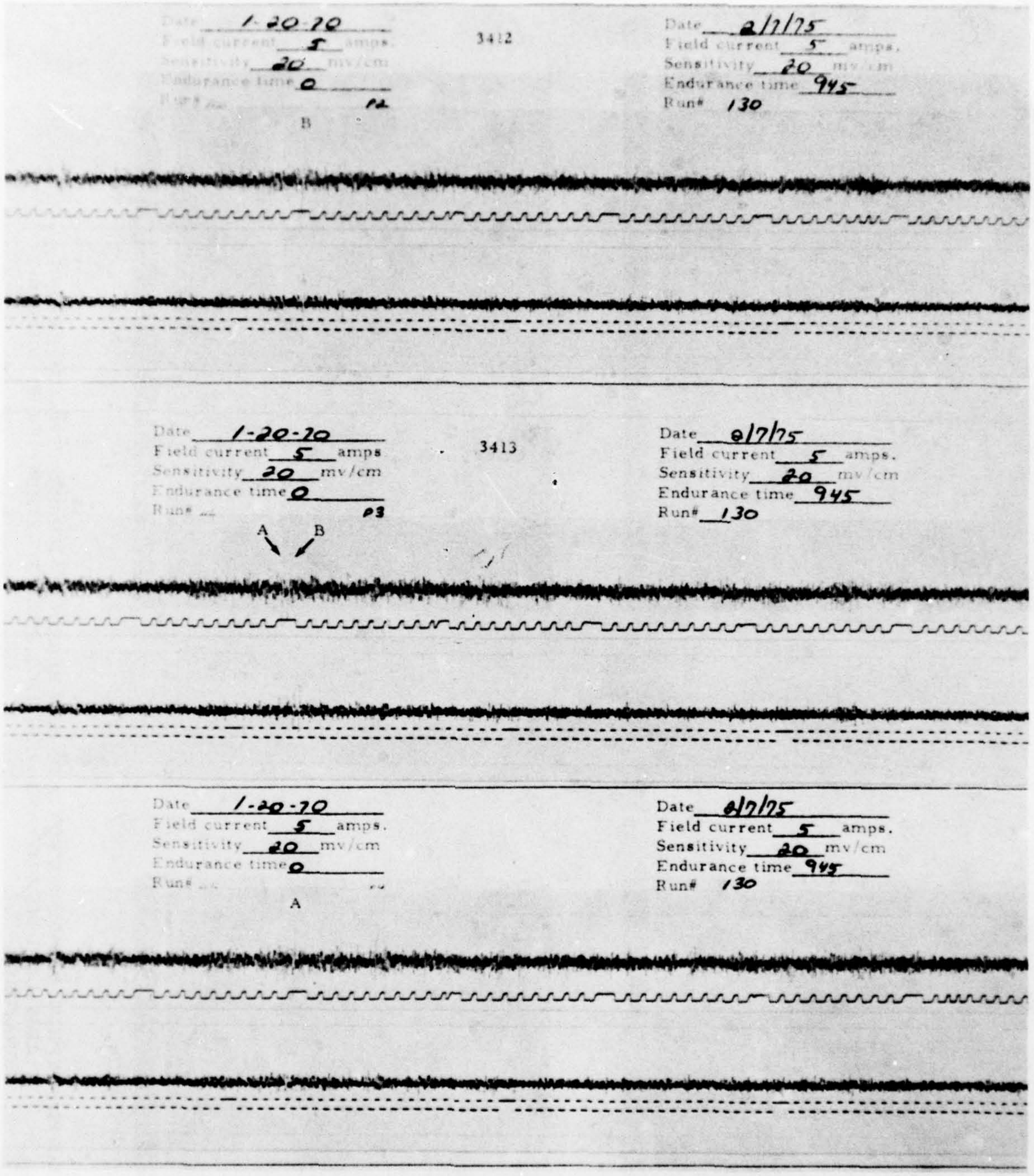


FIGURE 20. MAGNETIC PERTURBATION (CH) SIGNATURES INDICATING SUBSURFACE INCLUSIONS IN NEW J85-#2 BEARING S/N 06630

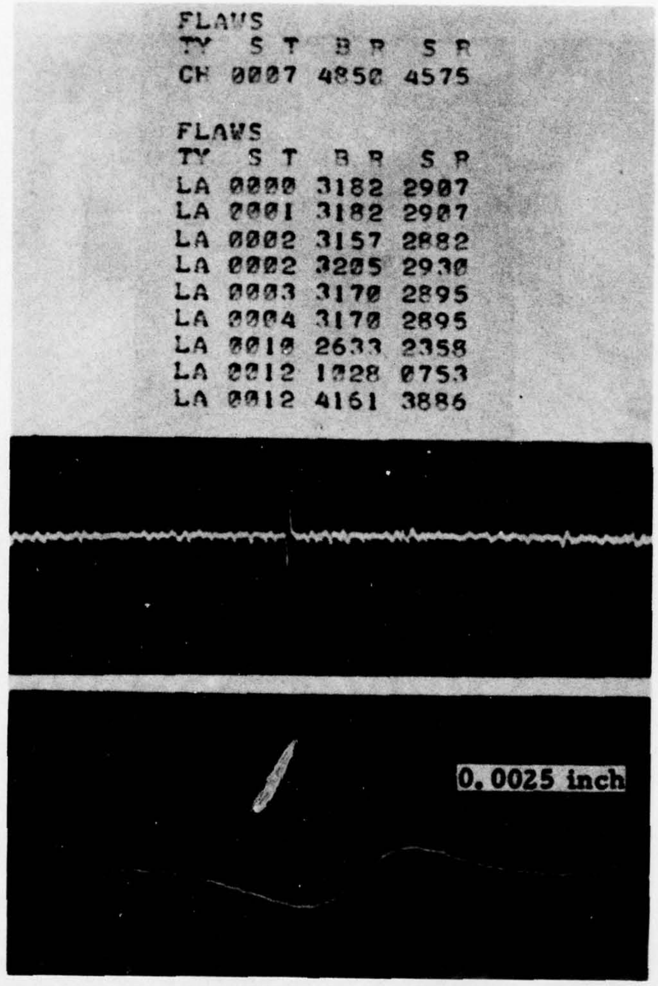


FIGURE 21. COMPUTER PRINTOUT AND ASSOCIATED MAGNETIC PERTURBATION SIGNATURE (CH) INDICATING SUBSURFACE INCLUSION IN J57-#4 BEARING S/N 493-1 (BEFORE ENDURANCE TEST)

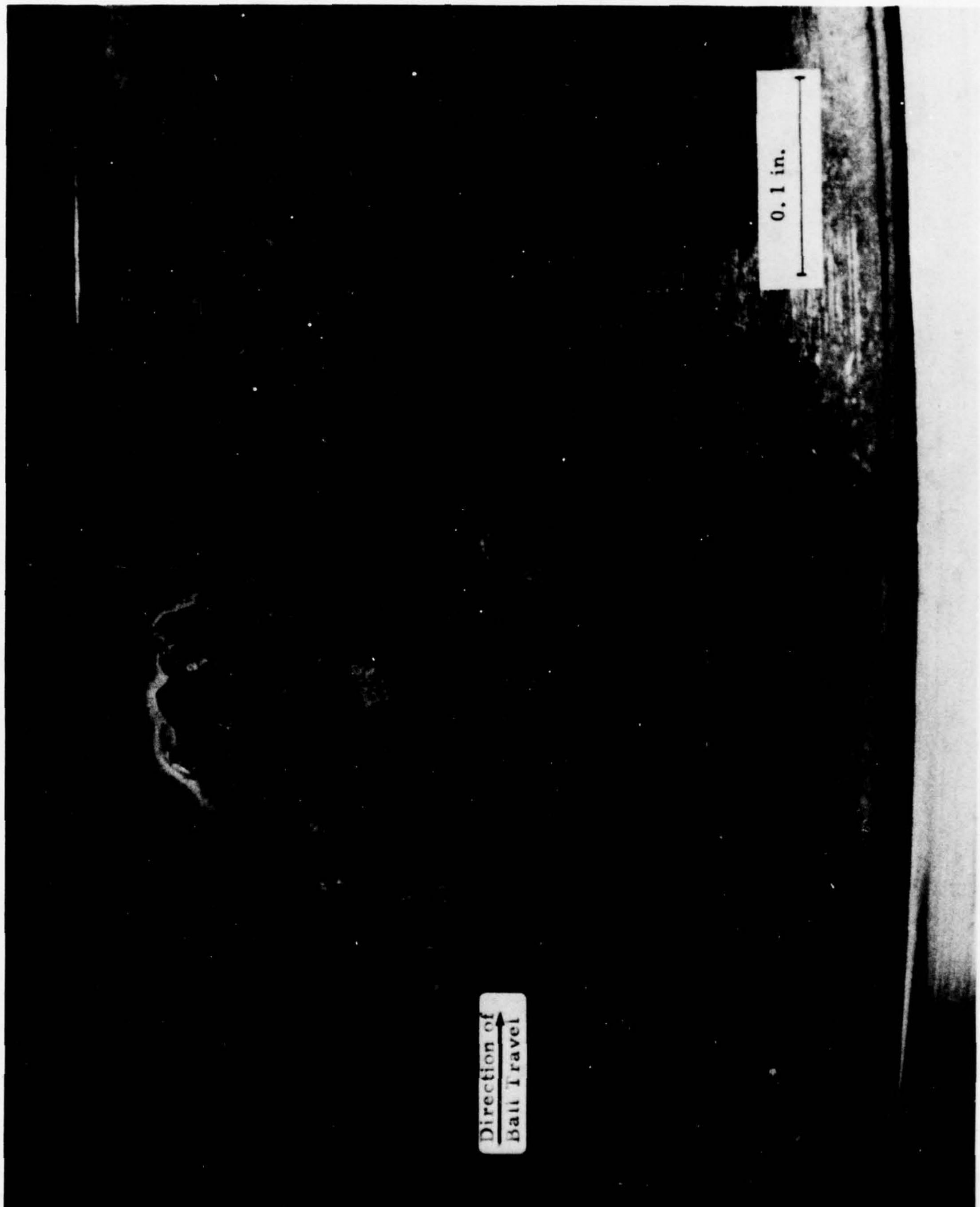


FIGURE 22. VIEW OF SPALL ON INNER RACE OF J57-#4 BEARING S/N 493-1 (AFTER ENDURANCE TEST)

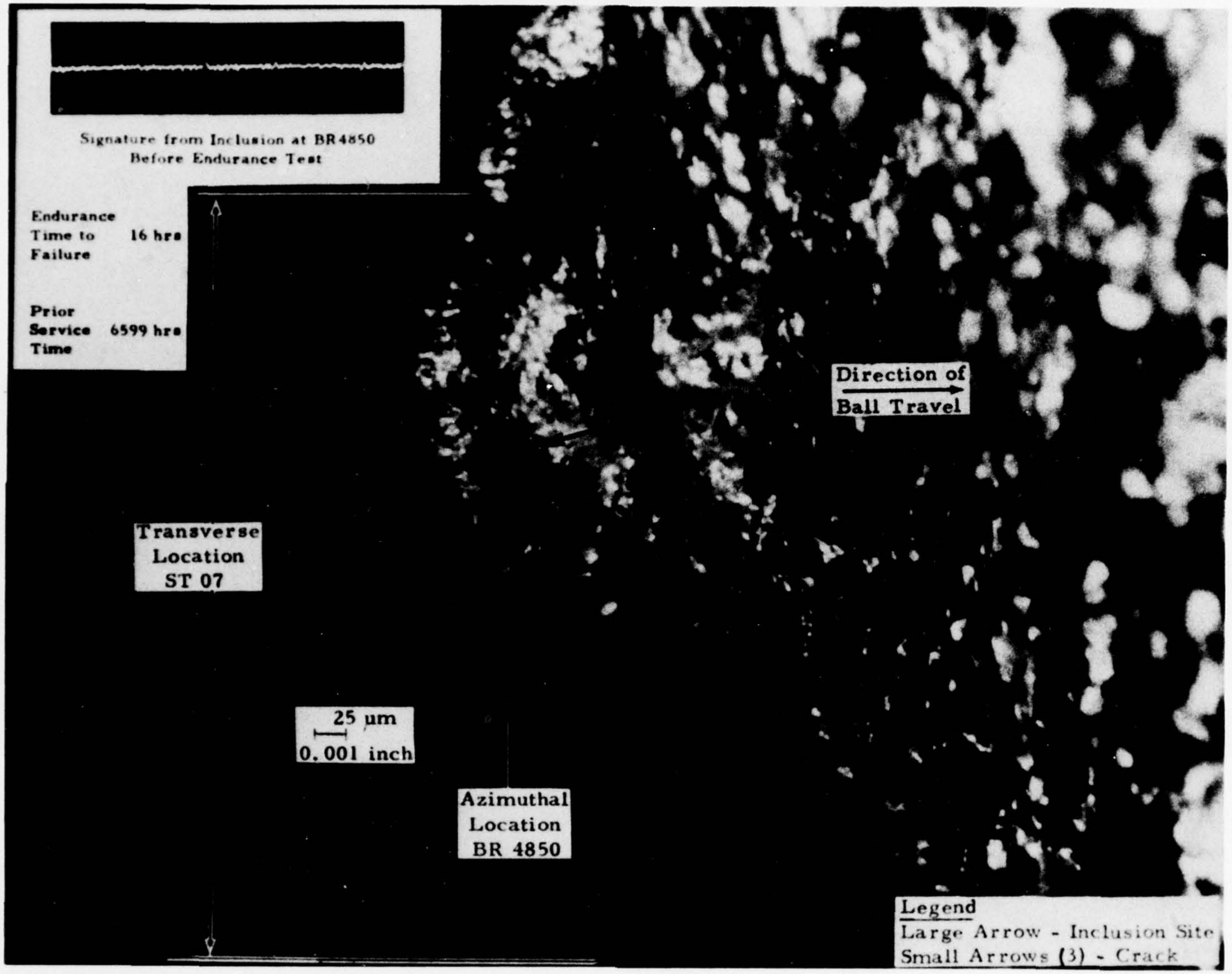


FIGURE 23. PRECISE CORRELATION OF SIGNATURE AND SPALL INITIATION LOCATION

CRACK DETECTION IN BOLTED JOINTS

by

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CRACK GENERATION

Fatigue cracks were generated from holes in sheet material by application of fatigue loading to one hole at a time. Fig. 1. From the cracked sheet material, a number of single shear two row lap joints were made. Fig. 2.

In order to produce not-through cracks originating from the contemplated faying surface following measures were taken:

a) By means of a fixture a static bending corresponding to about 0.45 σ_Y was superimposed.
b) The pin for application of the local fatigue loading was conical causing a very non uniform bearing through the depth of the hole.

About $2 \cdot 10^5$ load cycles of (2.5 ± 2.0) kN produced two opposite cracks with about 15 mm tip to tip distance. In the seven hole-pitches wide sheets, cracks were generated from all seven holes or from one edge hole or from one center hole. Fig. 3. After redrilling, reaming and countersinking, lap joints were made by installation of 6 mm steel bolts into the 2.5 mm 2024-T3 clad and anodized sheet material.

INSPECTION FOR CRACKS

Prior to a residual strength testing, the lap joints were subjected to nondestructive testing (NDT). Inspectors from three aircraft operators were employed to detect fatigue cracks. None of the cracks was visible from the outside of the joint. Fig. 2. No disassembly was allowed.

From the very beginning all inspectors selected the ultrasonics method to be the most suitable. The inspectors no. 1 through 3 made the search from the csk-side, while no. 4 made the search from the faying surface. The heads of the steel fasteners made the X-ray method inefficient for short cracks. For comparision, however, one complete X-ray examination was carried out. Trials with the Eddy Current method gave about 50 % success compared with the ultra sonics. In particular cracks growing from an edge hole towards the free edge were difficult to detect with Eddy Current. The Eddy Current application was not opptimized.

Fig. 4 shows the result of one NDT examination. The actual specimen numbering had no relation to the cracking pattern, i.e. was all different from the numbering in fig 4. In fig 5 the results from the complete examination are summarized. The efficiency of the X-ray method is very inferior to the ultrasonics. The good efficiency of the ultrasonics method is still more evident from the crack length measurements according to fig. 6. The ability to detect small cracks is visualized by fig. 7. Although one crack with an area of only 0.5 mm^2 was detected by two inspectors, another crack as big as 9 mm^2 was missed by three inspectors.

In addition, an NDT-specialist with experience from the field of civil engineering only, was given the opportunity to inspect these same specimens. He selected the X-ray method and did not find a single crack. His result is not included in fig. 5.

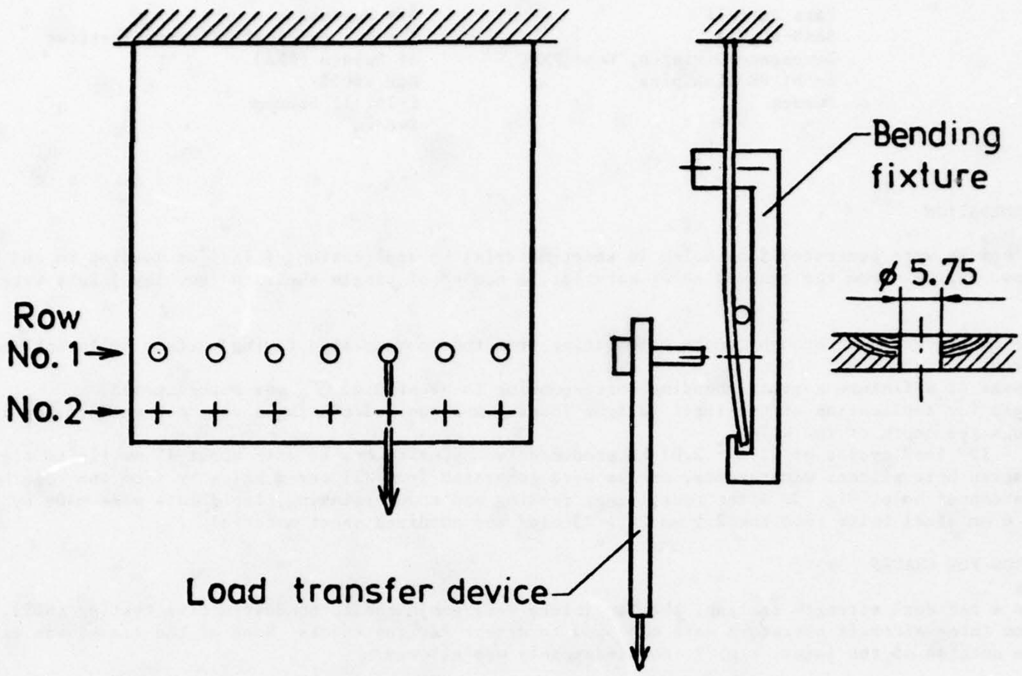


Fig.1 Generation of fatigue cracks

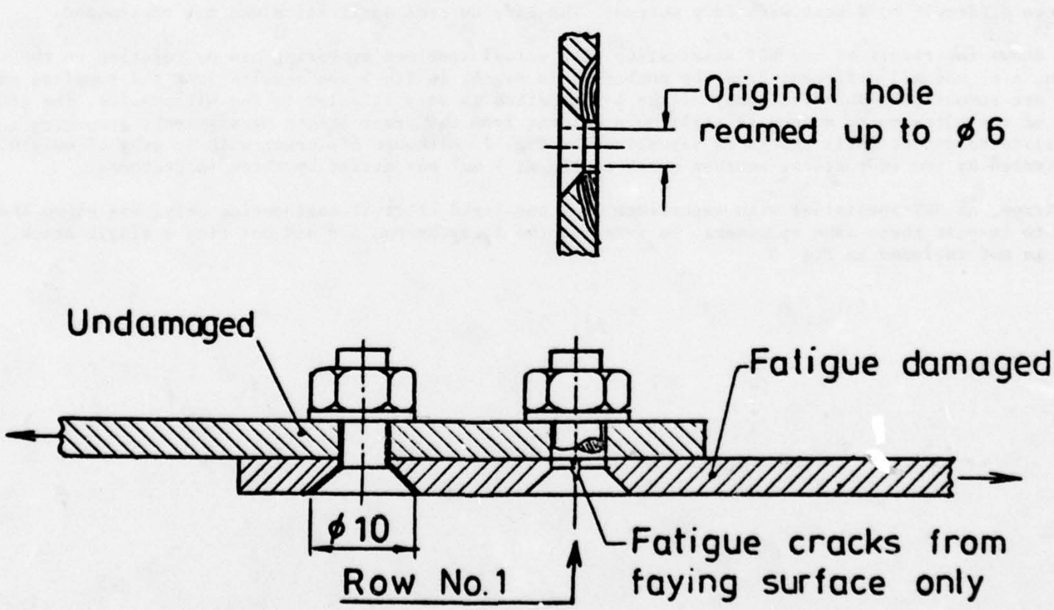
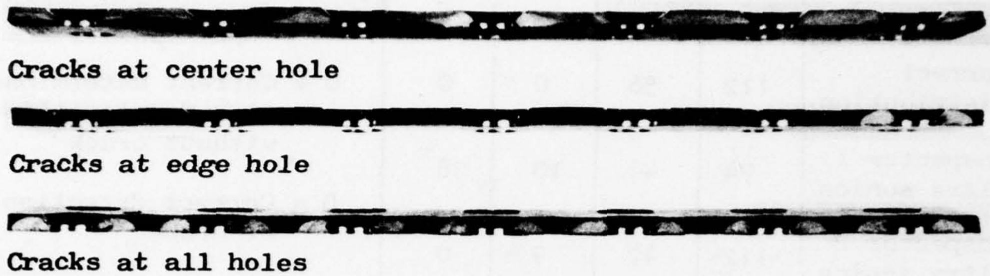


Fig.2 Assembly of a bolted joint using a cracked sheet member



Cracks at center hole

Cracks at edge hole

Cracks at all holes

Fig.3 Fracture surfaces

Specimen No.	Hole number and location, a ⟨○⟩ b													
	1		2		3		4		5		6		7	
	a	b	a	b	a	b	a	b	a	b	a	b	a	b
2	O	O	O	O	O	O	O	O	O	O	O	O	O	O
3	O	O	O	O	O	O	O	O	O	O	O	O	O	O
5	O	O	O	O	O	O	D	D	O	O	O	O	O	O
6	O	O	O	O	O	O	N	D	O	O	O	O	O	O
7	O	O	O	O	O	O	D	D	O	O	O	O	O	O
8	O	O	O	O	O	O	O	O	O	O	O	O	N	N
9	O	O	O	O	O	O	O	O	O	O	O	O	D	D
10	O	O	O	O	O	O	O	X	O	O	O	O	N	D
11	O	O	O	O	O	O	O	O	O	O	O	O	D	D
13	D	D	D	D	D	D	D	D	D	D	D	D	N	D
14	D	D	D	D	D	D	D	D	D	D	D	D	D	D
15	D	N	D	D	N	N	N	D	D	D	D	D	D	D

O = Correct determination for location without crack

D = Correct detection of crack

N = Crack not detected

X = Crack believed to exist at location without crack

Fig.4 NDT-results with ultra sonics. Inspector 4

	Number of markings			
	O	D	N	X
Correct distribution	112	56	0	0
Inspector 1 Ultra sonics	74	46	10	38
Inspector 2 Ultra sonics	112	47	9	0
Inspector 3 Ultra sonics	104	55	1	8
Inspector 4 Ultra sonics	111	47	9	1
Inspector 5 X-ray	107	13	43	5

O = Correct determination for location without crack

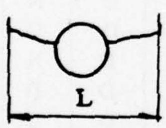
D = Correct detection of crack

N = Crack not detected

X = Crack believed to exist at location without crack

12 specimens with 168 possible crack locations examined by each inspector.

Fig.5 Survey of NDT-results



	Crack length (mm). Specimen No. 14						
	Hole no.						
	1	2	3	4	5	6	7
Correct crack length *)	17.6	16.1	16.5	15.2	16.4	14.6	15.4
Inspector 1	15	14	17	16	15	20	20
Inspector 2	17	15	17	17	18	19	15
Inspector 3	15	14	16	13	17	12	13

*) measured on the faying surface of the broken specimen

Fig.6 Crack lengths measured by ultra sonics

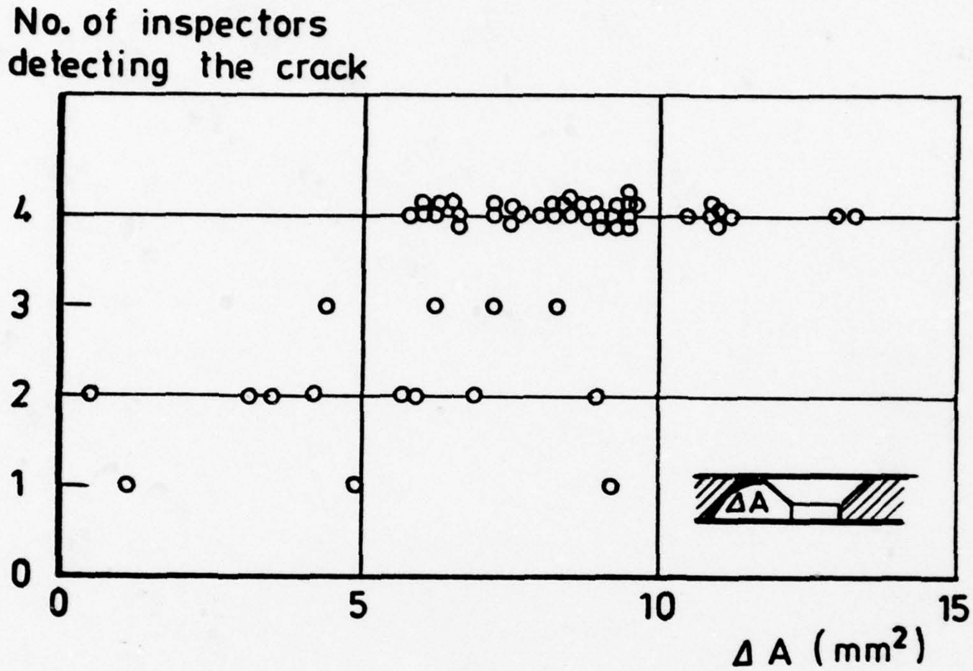


Fig.7 Ability to detect small cracks by means of ultra sonics

SESSION II
Part 2: Applications
Rapporteur's Report

by

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During the second part of Session II, there were four presentations on four very different topics. A synthesis of these presentations is almost impossible, but separate comments have been made on each of them.

First of all, we had Mr Uygur's paper, a remarkable synthesis of acoustical methods used in non-destructive inspection (NDI). Unfortunately, we learn from other specialists that acoustical methods have not yet found many practical applications in the aeronautical industry. One exception is the field of NDI of bonded structures, where tests as simple as the tap test, as well as more elaborate equipment using the principles of sonic resonance, are used.

In the field of metallic materials, it has happened that the human ear was a better receptor than more sophisticated equipment. An example: in the engine workshop we had to inspect compressor vanes and shrouds. The inspection was done with fluorescent penetrant but, before dipping the part into the penetrating oil, the inspectors used to knock gently over the different vane airfoils. Each time a crack was present in the airfoil, the pitch of the sound was different. Some trials were made to automate the process with electro-acoustical equipment. But finally, the inspectors prefer to rely on their ears.

The second presentation, by Richard Schütz, was devoted to the full-scale fatigue tests performed at the demand of aircraft manufacturers. As Mr Schütz points out, NDI and associated measures cause very high costs because of the extensive amount of manhours involved. The aircraft manufacturers now realize that it is possible to reduce the future NDI costs and at the same time to increase flight safety through full scale fatigue testing. These tests are able to determine the fatigue critical locations and the crack propagation behaviour of the critical components. From this data, a chart is established with the following inspection requirements: location of zone to inspect – most efficient NDI method – beginning of inspection – inspection intervals. This chart, as we understand, is a document internal to the aircraft manufacturer.

According to the conclusions of the simulated fatigue test, the manufacturer will send out a service bulletin which imposes an inspection campaign which may be associated with a part replacement campaign.

Operators usually receive service bulletins with as much pleasure as a taxpayer receives his income tax return form. Actually, the operator would prefer not to have any cracking problems at all, so no NDI (or at least to have the smallest possible amount of NDI work to do, that is to say, as long a period of time as possible between inspections). Now, if these campaigns are unavoidable, operators would prefer to have centralised inspection programmes of sub-assemblies, so as to avoid different inspection campaigns at different times.

And last, but not least, aircraft operators would appreciate a beter standardisation of NDI methods. Many improvements in this direction have been performed by engine manufacturers, who are now designing their engines with adequate openings which facilitate inspection work with a borescope or a gamma-graphic radioactive source.

The third paper was devoted to the NDI of bearings. Communications about this topic are rather unusual. In fact, much work has been done during the last years, at the manufacturing stage, to develop sophisticated inspection techniques. But not much has yet been published. Moreover the aircraft operators do not know very much about these techniques. They are still using the same old system that the Dutch were already using in the XVIIIth century for the inspection of their windmills' roller bearings; that is, visual inspection.

A short anecdote, about an incident which happened in 1977, will illustrate the subject.

A main bearing of a JT8 engine had to be inspected. The type of inspection to be carried out was a simple dimensional and visual check. The inspector removed the cover of the bearing, looked at the visible part of the cage and noticed nothing. The bearing was accepted. But in the meantime, it turned out that inspectors disassembling the engine discovered, in a drain of the engine oil circuit, some copper particles. These particles were sent to the laboratory; the chemical analysis disclosed that the particles were made of the same alloy as the cage of the main bearing.

According to this discovery, the main bearing was completely taken apart and, when the interior part of the cage became visible, it turned out that the cage surface had been locally worn by the balls. The wear was such that the bearing could still have been used for sometime without any trouble. But before the next overhaul, the engine would surely have experienced an in-flight shut down.

This anecdote shows that there is still work to be done in the field of bearing inspection, especially in the maintenance field. The CIBLE program is an interesting approach. Another approach would be chemical analysis of oil and filter particles.

Progress in the NDI of bearings could save an aircraft operator a lot of money, especially in the field of small bearings, which are often scrapped after one run, because of the lack of information on their reliability.

In the fourth paper, by Mr Jarfall, we find some very interesting statements, which can open the discussion about the training and qualification of NDT personnel.

A comparison is made between different NDT techniques and different inspectors, for a particular type of fatigue crack. In this instance, ultra-sonics were found the most suitable method. Would this be true in another country with differently trained inspectors? What would happen with another material and another type of crack; stress corrosion for instance?

I would particularly appreciate having Mr Bond's comments about his experience of NDT training at B.A.

DISCUSSION SUMMARY
Session II – Part 2

E.M.Uygur (TU)

I wish to add some comments to my paper, and I would like to add to Mr Van Averbeke's comments. Although the lateral frequency of the specimens is really beyond the audible range, this difficulty has been overcome by the use of suitable electronic instrumentation. The rate at which the sound intensity of a vibrating specimen decreases is a characteristic of the condition of the material, and the unaided human ear can determine differences as large as 20% in the decay time.

In recent years some commercial instruments have been produced for the dynamic testing of materials, and I would like to point out that dynamic testing presents a unique spectrum of applications from the microscopic to the macroscopic. Using dynamic techniques we can calculate the dislocation intensities, we can detect foreign atoms near dislocations, clusters of foreign atoms in the material and precipitates in the material, we can investigate the grain boundaries and grain size, we can determine the average grain size in a polycrystalline material, we can detect sub-microscopic cracks and in large assemblies we can detect flaws. Finally, in very large structures such as an aircraft, I think we may be able to find certain defects using the same dynamic testing method.

In view of the discussions and criticisms I have heard in this conference, I would like to say that the development of new and more effective techniques of inspection are needed and I suggest here that dynamic testing be applied to the complete aircraft. A full scale aircraft could be tested periodically after a given period in service instead of going rivet by rivet from one critical part of the aircraft to another. One has to excite the aircraft by sonic or ultrasonic vibrations, so that one can either measure the natural frequencies of certain parts or calculate the damping. In this way one can compare a service aircraft against a standard which has not been in service. Normal laboratory equipment can generally be used for this purpose. The only problem is that strong vibrators are needed for full scale dynamic tests.

R.J.Schliekelmann (NE)

After 25 years of experience in vibration and resonance testing, I agree only with a small part of what Dr Uygur has said. A great many parameters influence the resonant frequency of structures. If you know that only one parameter is present, then you can draw a conclusion, but if many parameters at the same time are present, then you are unable to do so.

C.P.Galotto (IT)

I would like to speculate for a little while on the philosophy of NDI. If we consider a specimen to be a system into which some form of energy is introduced, then we measure the output energy (which is not necessarily homogeneous with the input energy) and this must be correlated somehow with the engineering properties which one seeks to control. These properties can include crack size, stress concentrations, hydrogen content and so on.

In our discussions I have heard talk of microscopic defects like a mismatch of atoms, clusters of point defects or the density of network dislocations. Unless we can see the correlation, if any exists, between the modification of this microscopical property and the macroscopical engineering properties, then I think we are still at the stage of NDI development. In other words, we are still disregarding the point of view of the designer and the materials manufacturer, although it was the intention of this meeting to correlate the needs of the design engineer and the manufacturer with the possibilities in the field of NDI.

D.Kirk (UK)

I would like to know who is misleading whom with respect to ball bearings. I have been given the impression that the inspection of bearings is only slowly coming out of the dark ages, and yet my experience of bearing manufacturers is that they use sophisticated techniques for inspection. They put controlled levels of residual stress into the bearings, and they look at the metallurgical structure with particular respect to those phases which might alter the dimensional stability.

A Speaker

I would like to answer your point regarding the dark ages. This comment was concerned with the maintenance of bearings in an engine and not with their manufacture, and there is a big difference between these two aspects.

P.Pizzi (IT)

With reference to ball bearings, I would like to point out that FIAT have developed NDI methods during the past two years for observing wear particles. This is achieved by examining the shapes and concentration of wear particles, and is a very interesting non-destructive test of destructive particles.

R.J.E.Glenny (UK)

May I ask Mr Smith whether the techniques which he has described have reached the stage where they can be adopted by the bearing vendor?

R.T.Smith (USA)

That is not the case yet. The programme is a little beyond the construction of the hardware to enable us to collect data which should eventually lead to the interpretation of the signal.

M. Van Averbeke (BE)

I would like to hear the comments of Mr Bond on the paper presented by Dr Jarfall, and to learn what he thinks about the difference techniques of inspection for fatigue cracks.

A.R.Bond (UK)

There has been a considerable amount of work into the likelihood of detection of defects. What we would like, of course, is to be sure of 100% detection every time. Now the likelihood of 100% detection depends upon the man's training, his age, his experience, his education level and so on. In the USA they have found that it does not make the slightest bit of difference if the inspectors have 3 weeks training, 3 years training, how old they are or what sex they are, but we have had a look into this and we find that if a man is very highly educated the detection rate is also very high. Now where do you find your NDT men? Do you take them straight from the workshop floor, or off the street, or do you employ them when they come out of high school, when they come out of technical college, when they come out of university or when they have received their PhD? This is what the detection rate depends on.

In the USA, where they have a poor detection record among the inspecting organisations, they intend to improve their record by automation. The other way to do it may be to take a man with a low education level and give him a good training, but it is absolutely no use giving him a certificate unless you are prepared to do a certain amount of re-training. Once upon a time you could only detect corrosion when the component was almost completely failed, possibly by detecting a bulge in the outer surface. Then along came radiography and the detection rate improved; two years later low kV radiography was introduced, but when eddy current techniques came along, 1% corrosion could be detected. If we are going to certificate men once a year or once every two years, then they will be out of their depth because technology will have run away from the education level the man started at. I do not agree that the certificate should last for ever. We make sure that the inspector actually uses the techniques; if he does not, we remove his approval for that particular method of NDI.

C.P.Galotto (IT)

I would like you to explain why a PhD used as an inspector does not get tired or bored and thus misses defects in some important place.

A.R.Bond (UK)

Given just one task, I would not expect a highly educated inspector to miss any defects. But if the inspector is a man from a shipyard who is only used to welded structures, he would fail completely to inspect an aircraft structure properly.

C.P.Galotto (IT)

The purpose of automation in NDI is to make a complete test of all the components which have to be inspected, and to avoid subjective judgements. Again I do not understand why a PhD is better than the man in the street.

C.W.Hope (UK)

It is well known that Mr Bond and I agree on a lot of things but it is also known that I call his philosophy poppycock in this case. I am very concerned about operator fatigue, and I would like to ask how many of us (in view of the fact that we have a dinner tonight) would be able to carry out an intensive inspection at 9 o'clock tomorrow morning.

L.Jarfall (SW)

I think that the structural designer and the fatigue expert also have a great responsibility in relation to the success of NDI. If the designer does not tell the NDI people where to look, then the inspection will never be successful, since one cannot look everywhere. I think too little has been said about this problem; perhaps it should be discussed by the fatigue experts rather than by us, but I feel that the problem should be pointed out.

NON-DESTRUCTIVE INSPECTION OF COMPOSITE MATERIALS FOR AIRCRAFT STRUCTURAL APPLICATIONS

by

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SUMMARY

The defects which occur in composites often have no metallic equivalent and their effect on the mechanisms of fracture are less clearly understood. Also the response of composites to established NDI techniques has only recently started to be investigated. There is therefore a need to develop methods of finding, and quantifying, these defects and then to investigate their effect on the mechanical performance, so that suitable acceptance standards can be set.

Attention is concentrated upon fibre reinforced plastics with particular reference to CFRP (carbon fibre reinforced plastics). The capabilities and limitations of various techniques are briefly reviewed. Rather than review the various defects that can occur and the wide range of NDI techniques that have been employed to find them, attention is concentrated on those features that appear to the author to be of greatest practical interest. Difficulties in transferring laboratory techniques to prototype and production structural components are discussed and problem areas reviewed. Finally consideration is given to the role of acoustic emission.

1. INTRODUCTION

In order to guarantee the airworthiness of an aircraft it is necessary to be able to identify the defects which may be present in structural components and the importance of this task has motivated several significant developments in the NDI field. The current trend towards a damage tolerant design philosophy places even more importance on accurate NDI because it requires the NDI technique to be able to guarantee to find a given defect with a specified probability and degree of confidence and, having detected it, to be able to characterise it in such a way than its effect on the structural performance can be determined. The extent to which the available NDI techniques are achieving this end for metallic structures will be discussed in a number of papers at this Conference; it is probably fair to say, however, that with metallic materials our knowledge of the fracture process is such that we can usually stipulate what type and size of defect is acceptable in a given situation. Shortcomings certainly exist in our ability to detect and characterise such defects, but there is a large background of accumulated information and expertise on which we may draw. Also developments in structural NDI outside the aerospace field are usually concerned with metallic materials and there is a useful interchange of ideas.

For composite materials, however, the form of defect is often entirely different and the mechanisms of the fracture process are more complex. The result of this is that the effect of the various defects on the mechanisms of fracture are at present less clearly understood. In addition the response of composite materials to the established NDI methods has only been seriously investigated comparatively recently, and some inadequacies have clearly been revealed. It should, however, be emphasised that NDI methods must not be studied in isolation, because the fundamental need is for the user to be able to differentiate between those defects which are potentially detrimental to the performance of the structure and those which may be ignored with equanimity. In order to achieve this it is necessary to ensure good collaboration between the design, fabrication, NDI and mechanical or structural testing groups.

Now the term composite materials embraces a wide range of materials having very different mechanical properties; in this paper however, we are concerned with aircraft structural applications and this mainly limits consideration to epoxy resins reinforced with boron, carbon (graphite) or glass fibres. Boron-epoxy has received little attention in the UK and, although there has been a large amount of work on it in the USA, economic factors suggest that there also CFRP will predominate for the majority of future applications. GRP (glass fibre reinforced plastics) have tended to be used for secondary structure for which less stringent quality control is required. There is however the important application to helicopter rotor components. Attention in this paper will therefore be concentrated on CFRP but reference will be made to GRP where appropriate.

There have been many excellent reviews of the various defects that can be found in composite materials and of the wide range of NDI techniques that have been employed in an attempt to find them[1-8]. This paper will not attempt to summarise these but will instead concentrate on those features that appear to the author to be of greatest practical interest.

2. TYPES OF DEFECT

In this section it will be assumed that the defects considered are those arising as a result of the fabrication process or those that develop in service. Poor mechanical performance can of course arise as a result of poor quality raw materials and NDI techniques do have a part to play here in, for example, infra-red analysis of the resin. The majority of testing at this stage is however essentially destructive and batch certification procedures inevitably involve mechanical tests on samples of the material in its fabricated form. Similarly NDI procedures may be applied as part of the process control procedure during

the fabrication process. These procedures would include such things as the use of eddy currents to monitor the thickness of adhesive priming coatings on metallic substructure[8] and the use of back lit tables for improved visual inspection during lay-up.

2.1 Fabrication defects

There are many ways in which a composite can depart from a perfect state and the definition of a 'defect' must be to some extent arbitrary, since features which are quite acceptable in one application may cause severe degradation in another. Nonetheless with CFRP there are a number of features which have been identified as potentially detrimental to the mechanical strength. These are listed below and it may be seen that some of the defects (1, 2, 3, 6, 7) can occur in any type of CFRP fabrication, whilst the remainder is specific to components laid up from individual plies of 'pre-preg'. These are sheets of partially cured resin containing a uniform distribution of unidirectionally aligned fibres.

1 void content (porosity)
2 state of cure of the resin
3 condition of the fibre-matrix interface
4 delaminations
5 translaminar cracks
6 foreign inclusions
7 fibre volume fraction
8 fibre alignment within a ply
9 orientation and lay-up order of the plies
10 ply end-butt joints
11 overlap or lack of side-butt between plies.

All the factors listed above acting singly or in combination can affect the structural performance of a component. However the extent to which any combination of defects will prove detrimental is governed by the geometry (including lay-up order) of the structure, the exact location and orientation of the defects, the nature of the applied stress field and the environment in which the component is required to operate. There is unfortunately a serious lack of information on such factors. The NDI specialist therefore tends to concentrate on those defects that he can find.

2.2 Bonding defects

As with metallic structures most composite aircraft structures are fabricated from a series of components and although it is proving increasingly feasible to use conventional mechanical fasteners a large number of components are built up by the use of adhesive bonding. These bonds may be between composite and composite, composite and metal, or composite and sandwich core material. In a few instances the adhesive bond may only be acting as a filler and have little structural significance but in most cases the integrity of the bond is as important as the integrity of the composite material itself. The current state-of-the-art of aircraft adhesives has been reviewed by Cotter and Hockney[10]. A comprehensive list of possible bond defects has been compiled by Shelton[9], but for NDI purposes they may usefully be categorised more briefly as follows.

(1) Adherend geometry

This includes incorrect shaping of the adherends causing variations in the gap to be bridged by the adhesive, inclusion of foreign bodies and damaged or incorrectly assembled core material.

(2) Adherend preparation

This covers the use of the wrong mechanical or chemical surface preparation procedure or subsequent contamination.

(3) Adhesive geometry

This includes absence of adhesive, extra adhesive layers, gaps and small inclusions.

(4) Adhesive condition

This covers the use of an incorrect adhesive, incorrect cure procedure, resin used beyond its shelf life etc.

(5) Interface condition

This may vary from a gross defect such as the presence of an unremoved release paper to the gradual weakening of an interface by the preferential migration of moisture.

The effect of the above categories of defect is to reduce either the cohesive strength (ie the inherent strength of the adhesive itself) or the adhesive strength (ie the strength of the bonds across the interface between the glue line and the adherend). NDI procedures can often detect or even quantify changes in the above parameters, but it will be seen later that there is some difficulty in relating such changes to the structural performance.

2.3 Defects arising from in-service and environmental damage

In-service damage is caused principally by static overload, impact or fatigue, although other mechanisms such as creep and overheating are possible. This damage may take a number of forms varying from microscopic failures such as fracture or buckling of the fibres, through interface failure and matrix cracking, to macroscopic events such as delaminations and visible cracks. There are, in addition, the

changes in material properties caused by the environment in which the aircraft is required to operate. Damage from lightning or bird strikes, rain or hail erosion and the impact of debris on rough runways can occur with varying degrees of severity. Less obvious but equally important is the ingress of moisture caused by exposure to hot moist atmospheres for long periods and contamination with fluids.

Evidence to date based on composites with epoxy resin matrices[11] suggests that most of the fluids commonly found in aircraft such as hydraulic fluids, fuel and lubricants have only a minor effect on the material performance; the composites were however not under stress when exposed to these fluids. It has been demonstrated, however, that they can produce a degradation in the properties of some adhesive bonded joints, although this degradation is in fact significantly less than that which can arise due to moisture ingress. It is rather disturbing to find that some of the fluids used in NDI can themselves cause such degradation. Quite recently the skin-to-core bond was checked on a component having a CFRP skin and a 'Nomex' core; neoprene rubber loading pads had previously been bonded to the outside of the skin using an acrylonitrile adhesive. Two separate NDI techniques were employed each one using a different couplant. First the Fokker Bond Tester was used with a commercial ethylene glycol based anti-freeze as couplant and then this was wiped off and, some weeks later, a little machine oil was used to couple an ultrasonic contact probe. It was later noticed that some of the loading pads had become detached and subsequently investigations[12] showed that whilst either fluid acting alone was comparatively harmless a combination of the two could cause severe degradation of the adhesvie bond attaching the loading pads to the skin.

The effect of moisture ingress continues to cause concern in many composites[13]; not only does moisture migrate along the fibre-matrix interface and weaken the interface bond, but it also diffuses through the resin itself and the rate of diffusion is much increased if voids are present. The use of protective coatings can only delay, but cannot stop, this process. The usual environmental changes encountered in service have no effect on a dry composite, but once moisture is absorbed significant damage can occur and the moisture uptake is increased. This damage arises because the entrapped moisture can freeze at low temperatures or vaporize at the high temperatures encountered during a supersonic dash. It can be seen therefore that there is a clear need to monitor the degree of moisture absorption. Water ingress on a macroscopic scale can also cause problems, especially with honeycomb constructions; this problem is not however unique to composites.

Much the same situation arises with adhesive bonded joints between composites, the adhesive bond line being somewhat similar to a resin rich layer. Not a great deal has so far been published on the mechanisms involved but it is clear that moisture absorption will degrade the quality of the bond[15]. In metal-to-metal bonds moisture diffuses through the polymer but tends to migrate preferentially to the interface and to interact with the oxide surface finish to form a hydrated oxide which has poor cohesive properties. The result of this is to form points of weakness at the interface which can result in corrosion crevices which fill with water. The seriousness of this problem for some adhesives can be illustrated by the fact that a series of epoxy polyamide adhesive joints under moderate stress in hot wet conditions all failed within two years. It seems reasonable to assume that composite-to-metal joints will suffer in much the same way.

3. NDI TECHNIQUES

Many of the techniques used on metallic materials also have some application to composites and these have been summarised in a convenient form by Shelton[9]; the author has also presented a brief general review elsewhere[16]. In this section therefore, rather than review them again technique by technique, a number of problem areas will be considered and practical difficulties in applying quantitative NDI will be discussed.

3.1 Inspection of sheet material

The simplest and most widespread aerospace application of CFRP is in the form of sheet material for the skins of a number of different components varying from control surfaces to engine pods. These skins are multi-laminate angle-ply fabrications with a varying number of laminates.

A great deal of the NDI development has been done on composite material in this form and attention will therefore be concentrated upon it. The limitations that more complex forms of construction impose on the capability of NDI will be discussed later. It should also be noted that, although many of the early components were fabricated by moulding the sheet material to the required shape and then bonding the fully cured sheet to the required substructure, there is a growing tendency for the curing of the composite and of the bonded joint to be effected in a single operation. This inevitably makes the inspection more difficult to carry out and in general reduces the accuracy obtainable.

3.1.1 Ultrasonic inspection techniques

The technique which has proved to be most generally useful in this application is ultrasonic inspection. The easiest way of assessing material quality is to scan the sheet and to measure the attenuation induced into an ultrasonic beam transmitted through it. This can be done by a single transmission of the beam and the use of a pair of probes held in a calliper (Fig 1a), but it is often convenient to use a single probe as both transmitter and receiver and to let the ultrasonic beam return through the specimen either by using a reflector plate (Fig 1b) or by examining the back surface echo (Fig 1c). There must be a constant degree of coupling between the probes and the specimen and for many specimens this is most conveniently achieved by immersion in a water bath. For very large specimens, however, 'jet probes' must be used (Fig 2). A block diagram of suitable equipment is shown in Fig 3. The probe manipulator is connected mechanically or electrically to a recorder pen and the attenuation changes are displayed on a C scan record, which presents the data in the form of a plan view of the specimen with various pre-set attenuation levels shown as finite changes in trace density. A typical C scan is shown in Fig 4.

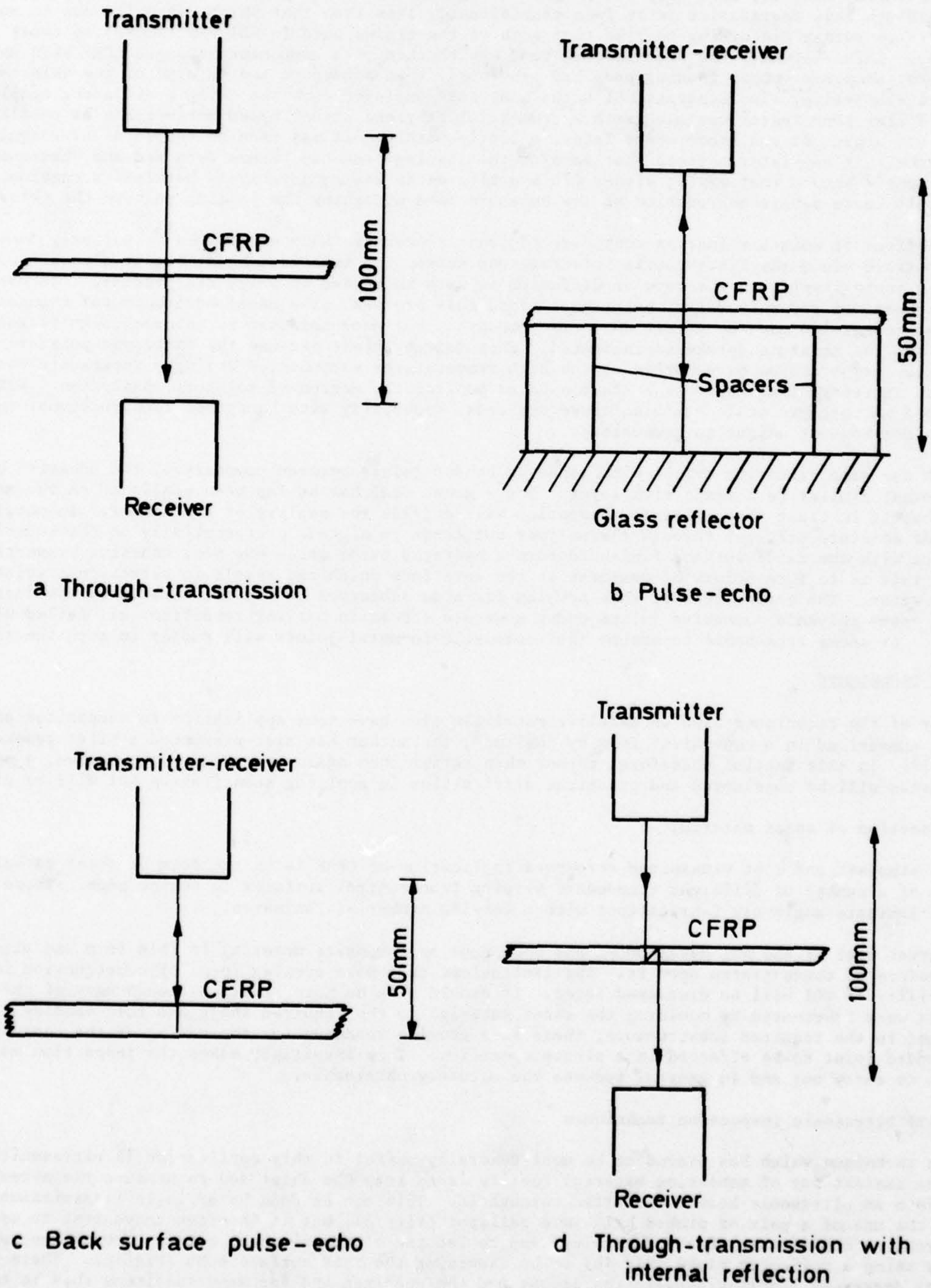


Fig 1 Alternative ultrasonic inspection procedures

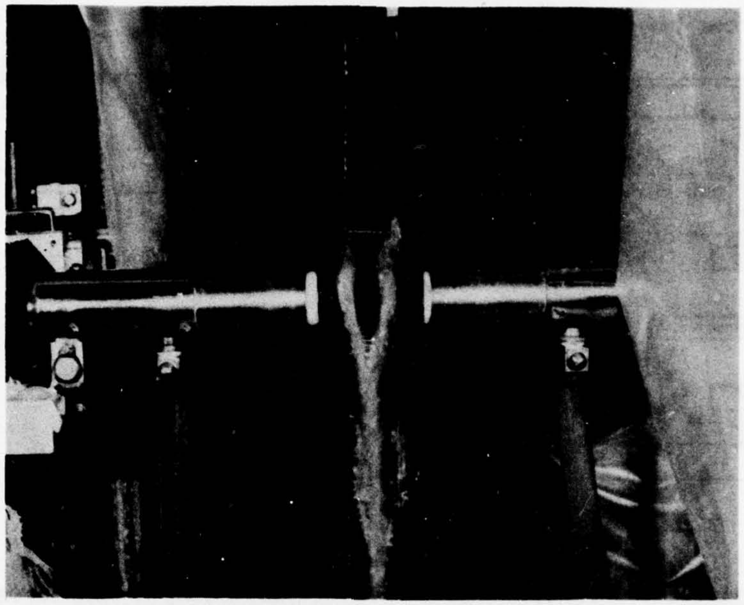


Fig 2 An ultrasonic jet probe
(courtesy of the British Aircraft Corporation Ltd)

What matters, of course, is what causes the attenuation and what level of attenuation is acceptable. The author has discussed this at some length elsewhere[17] but the principal factors governing it are -

- i delaminations
- ii the void content, V_v
- iii the fibre volume fraction V_f
- iv surfaces losses.

The state of cure of the resin will also affect it but once the optimum curing cycle has been established then monitoring of the autoclave temperature and examination of control samples should reveal any inadequacy of cure, and this has not in practice proved a problem. Now delaminations are, by definition, between individual plies and they are thus aligned parallel to the surface of the sheet and give a detectable back echo which may be displayed on an oscilloscope (A scan). Fig 5 shows how the use of quite high frequencies (10 MHz) and a focused probe enables the through-thickness depth of a delamination to be determined accurately. The size of delamination that is detectable depends of course on the area over which the ultrasonic beam integrates. Whilst a focused beam will give the necessary resolution it can cause problems in practice because small variations in probe to specimen distance can introduce unacceptable variations in attenuation. An alternative which avoids this difficulty is to use a simple stop in front of a parallel probe (see Fig 6). A standard 10 mm diameter plain probe with a centre frequency of 7.5 MHz was for example found[18] to integrate effectively over an area 6 mm in diameter; the addition of a 6 mm diameter stop reduced this area to one of about 2 mm diameter. Such a probe could detect a delamination 0.15 mm in diameter. Translaminar cracks (ie cracks in one ply parallel to the fibres and normal to the plane of the sheet) can also be revealed on a C scan by the use of high resolution probes. There is however a possibility of confusing them with other defects which can occur in narrow bands aligned with the fibres (such as resin rich areas at a side butt joint between sheets of pre-preg) and in cases of doubt it is best to investigate the area further with a pair of conventional shear wave contact probes.

If there are no significant delaminations then the attentuation suffered by the ultrasonic beam is attributable either to surface losses or to internal losses caused by reflection and scattering mechanisms usually at voids; internal damage will also increase the attenuation but this is a service problem and will be discussed later. The total attenuation for a sheet of thickness t may therefore be expressed as -

$$\text{through transmission} \quad A_T = A_S + \alpha t$$

$$\text{reflector plate pulse echo} \quad A_T' = A_S + A_S' + 2\alpha t \quad .$$

The important parameter to be measured is not the total attenuation A_T (or A_T') but the absorption coefficient α , which is usually expressed in dB/mm. It is therefore necessary to determine and subtract the surface loss term A_S (or $A_S + A_S'$). If the surface is of even texture and not too greatly curved this may be done by measuring A_T on a series of specimens of different thickness and extrapolating to

1 Trigger unit
2 Pulse generator
3 Transmitter
4 Receiver
5 Attenuator
6 Narrow band amplifier
7 Gate
8 Time base control
9 Proportional output unit
10 Quantiser
11 Recorder

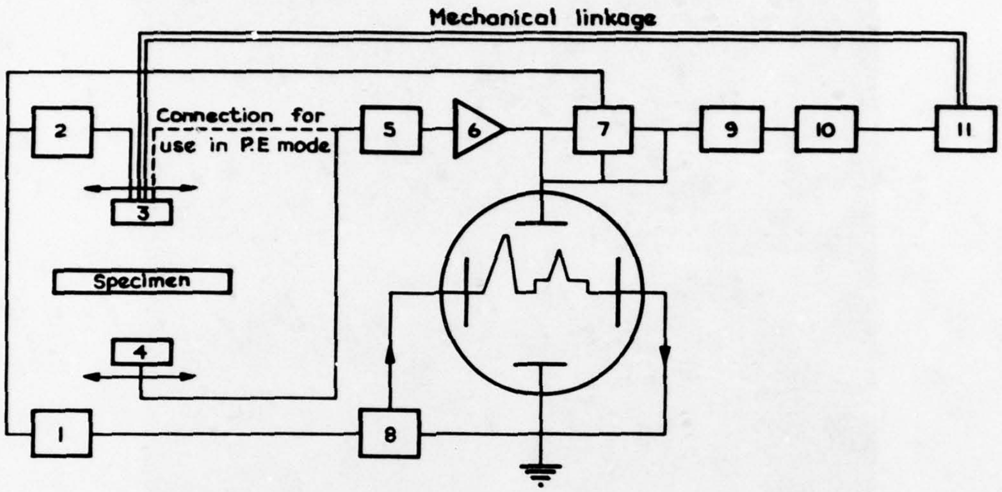


Fig 3 Block diagram of typical ultrasonic equipment

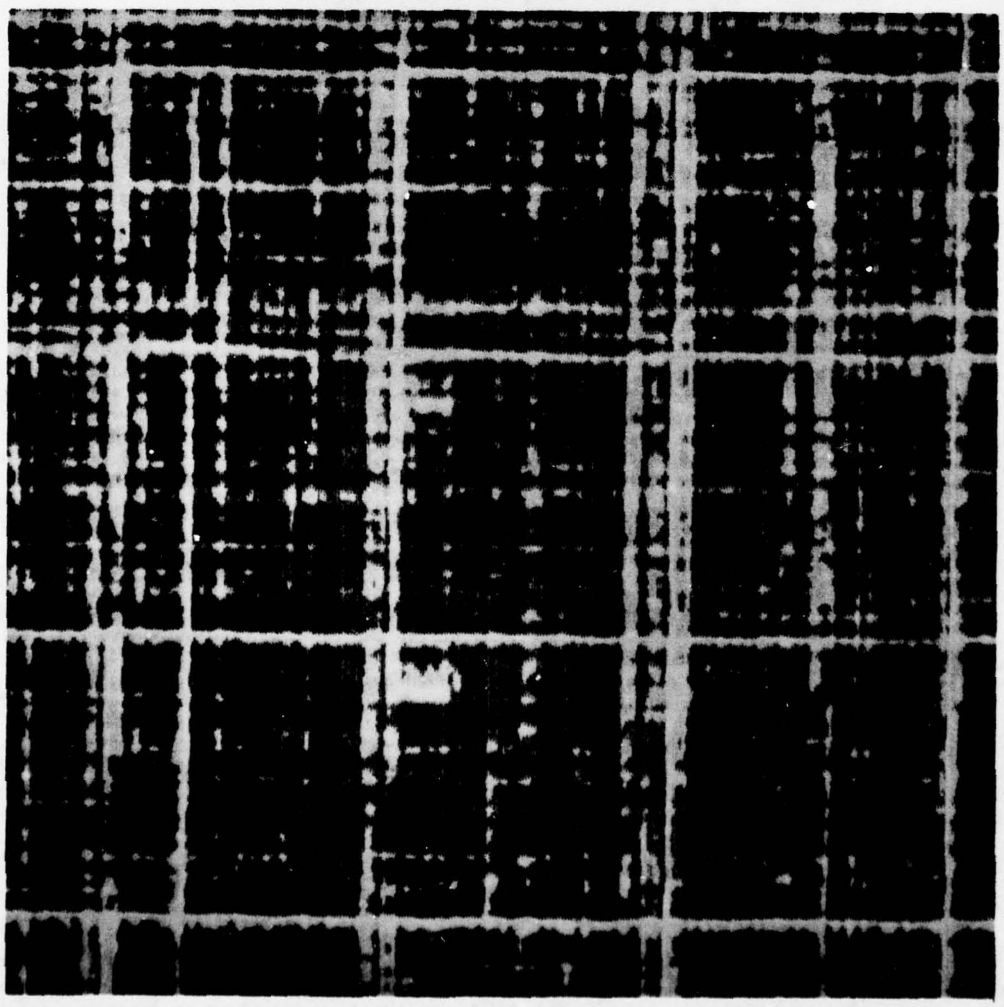
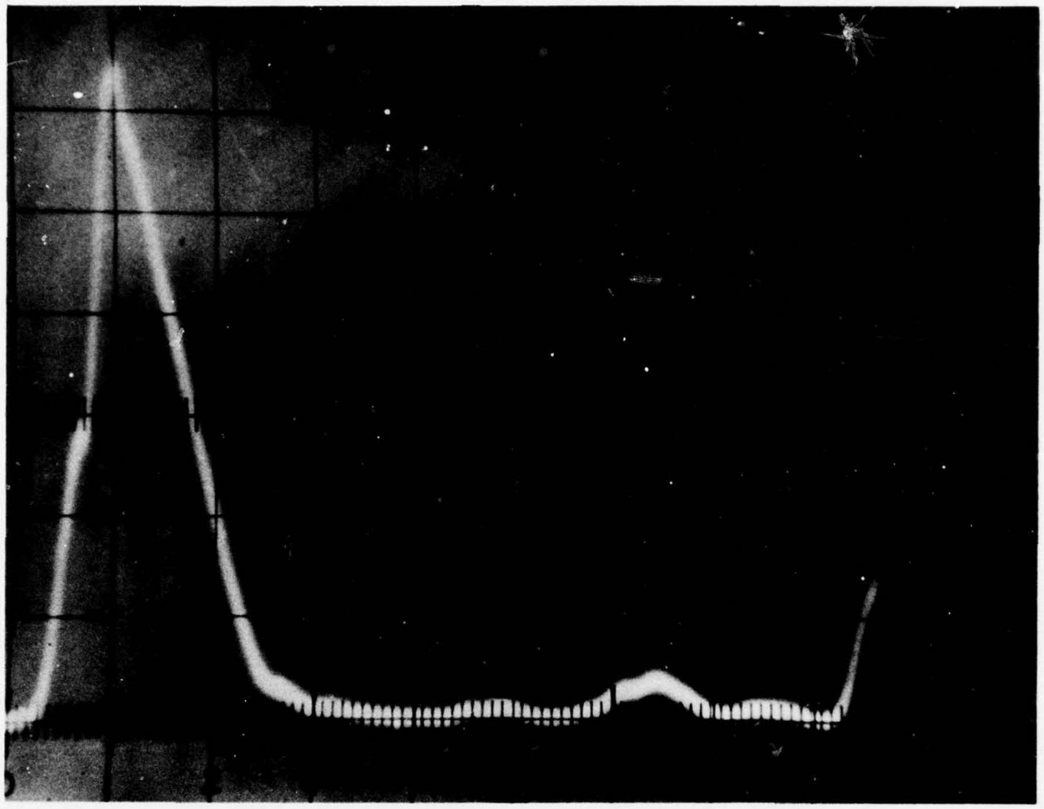
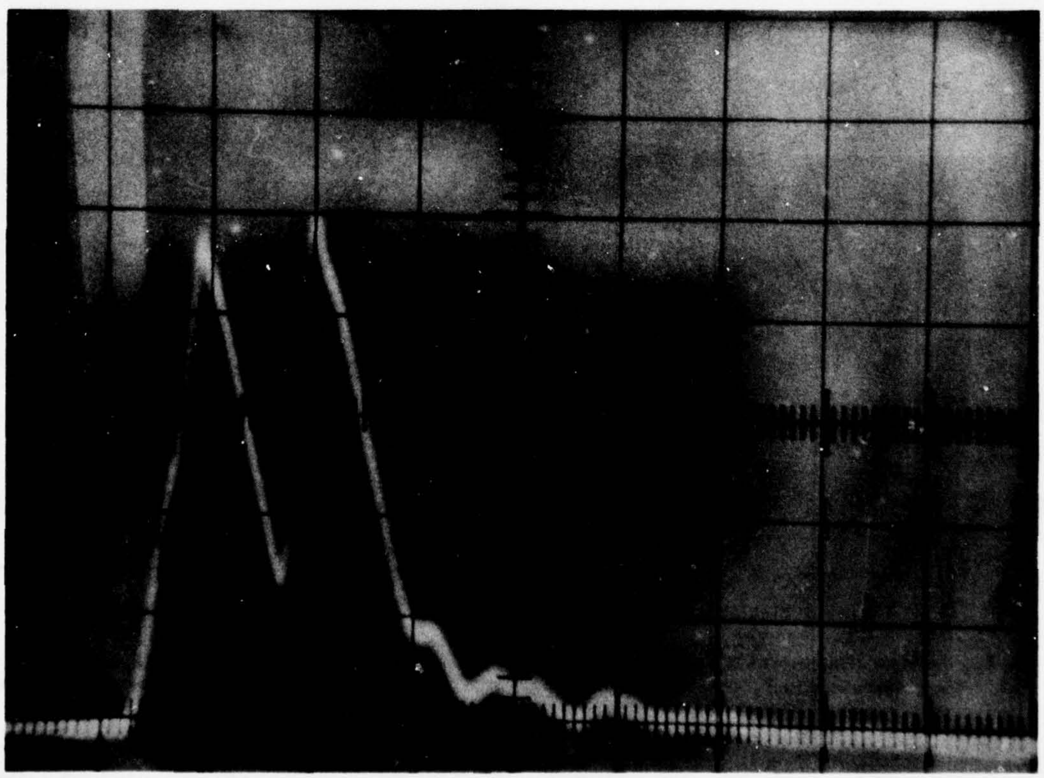


Fig 4 Ultrasonic C scan of a 0°-90°CFRP laminate laid up from 3in wide tape

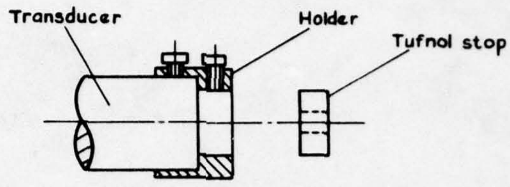


a Front and back surface echoes



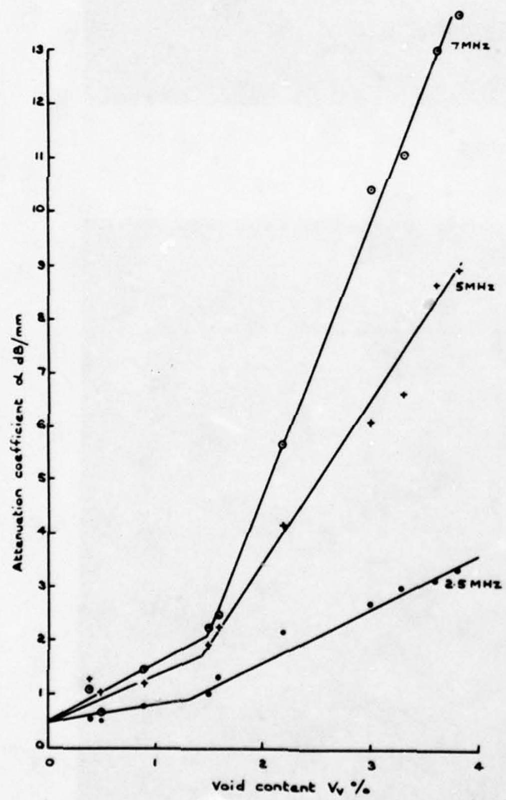
b Echoes from the front surface and a delamination

Fig 5 The A scan presentation may be used to reveal delaminations



b Narrow beam unit

Fig 6 Transducer fitted with a simple stop to produce a collimated beam



Replot of Fig 8 using a Bi-Linear curve fit

Fig 7 Variation of ultrasonic attenuation with void content

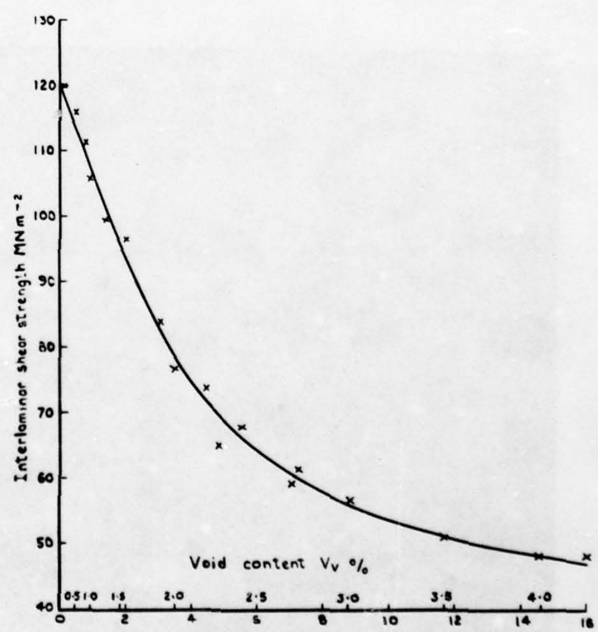


Fig 8 The interlaminar shear strength of uni-directional CFRP may be related to the ultrasonic attenuation and hence to the void content

zero thickness to give A_S [18]. An alternative method proposed by Teagle[19] may be performed *in situ* on the specimen but requires readings of attenuation to be taken by the techniques shown in Fig 1a and b and also by an additional technique shown in Fig 1d. Using techniques such as these the surface loss terms can be determined to an accuracy of about ±0.1 dB, typical figures for A_S and $(A_S + A_S')$ being 1.4 dB and 5 dB respectively. Now α varies from about 0.5 dB/mm for high quality material to about 3 dB/mm at the limit of acceptability, so it can be seen that for sheet material a few mm thick it is important that the surface losses do not vary too much from point to point if an accurate assessment of quality is to be made. Adequate uniformity in terms of surface texture and surface profile is in fact usually obtained on current sheet material, but uneven fibre distributions in earlier pre-pregs resulted in a rather convoluted surface which introduced quite significant errors into the attenuation measurements. Similar problems will be seen to occur with components of more complex geometry.

Although there are local changes in V_f, the fibre volume fraction, the quality of pre-preg currently being produced means that there is very little variation in V_v from point to point when integrated over the area interrogated by the ultrasonic beam. Any changes in attenuation caused by changes in V_f are usually masked by the changes due to the void content, V_v. Only when a high resolution probe is used on good quality material can these minor changes be seen.

3.1.2 The significance of defects and the establishment of acceptance standards for ultrasonic inspection

The important question that we are now faced with is what type and severity of void content is present and what effect does this have on the mechanical strength? The usual way of measuring void content is to measure the fibre and resin densities and then to use the acid digestion technique; in this way a calibration curve such as that in Fig 7 may be derived. For reasons discussed in Ref 18 such a curve is not as accurate as might be desired, but it does enable the effect of void content on the mechanical properties to be investigated. It is however extremely difficult to produce laminates which are of uniformly poor quality and such a relationship requires the mechanical test specimens to be cut from specific areas of the sheet and to have quite short effective lengths. Fig 8 shows such a curve relating the interlaminar shear strength to the absorption coefficient, and hence to the void content. The compilation of these results was rather time consuming and there is at present not a great deal of published data on these relationships.

One of the factors causing confusion is the fact that microscopic examination has revealed that a given attenuation could be caused by one or two isolated large voids or by a fairly uniform distribution of small voids. Clearly the effect of these two types of defect on the mechanical properties is unlikely always to be the same and it is therefore undesirable or possibly dangerous to give an arbitrary calibration between absorption coefficient and void content. To avoid this the concept of specifying the material quality in terms of an 'equivalent distributed void content' (EDV) has been introduced. For each material a curve such as that in Fig 7 must be established. Because of the difficulty in obtaining an exact destructive measure of void content it is unlikely that all laboratories would derive exactly the same curve so in the UK all the interested laboratories in the aerospace field have agreed on a series of standard curves for composites fabricated from each of the commonly used pre-preg systems. Attenuation measurements taken on sheet material of any given thickness can then be expressed in terms of an EDV to give a measure of quality. A given EDV can, however, correspond to more than one type of void distribution and a library of possible microstructures is now being built up. Fig 9 shows a few examples from the library being built up on material with an HC 3501 epoxy resin matrix.

In the longer term it is highly desirable to be able to distinguish between the various forms of microstructure giving the same EDV and it is likely that improved signal processing techniques will enable this to be done[20-22]. At present it would appear that examination of the frequency spectrum of the combined front and back surface echoes may well prove a useful method. Such advanced techniques may not yet be justified for more complex components but the advent of computer controlled automatic scanning and data processing systems[23] means that it is quite feasible to apply them to sheet material. At present, however, there is only limited evidence on the effect of these various microstructures on the static mechanical strength properties and a great deal needs to be done in the fields of fatigue and environmental testing before definitive statements can be made on the degree of acceptability of a given defect. It is also clear that improved NDI must form an integral part of such investigations.

In the meantime, however, acceptance standards must be laid down based on the evidence available to date. In terms of ultrasonic inspection these will mean that the designer will have to specify for each area of a particular complex skin fabrication -

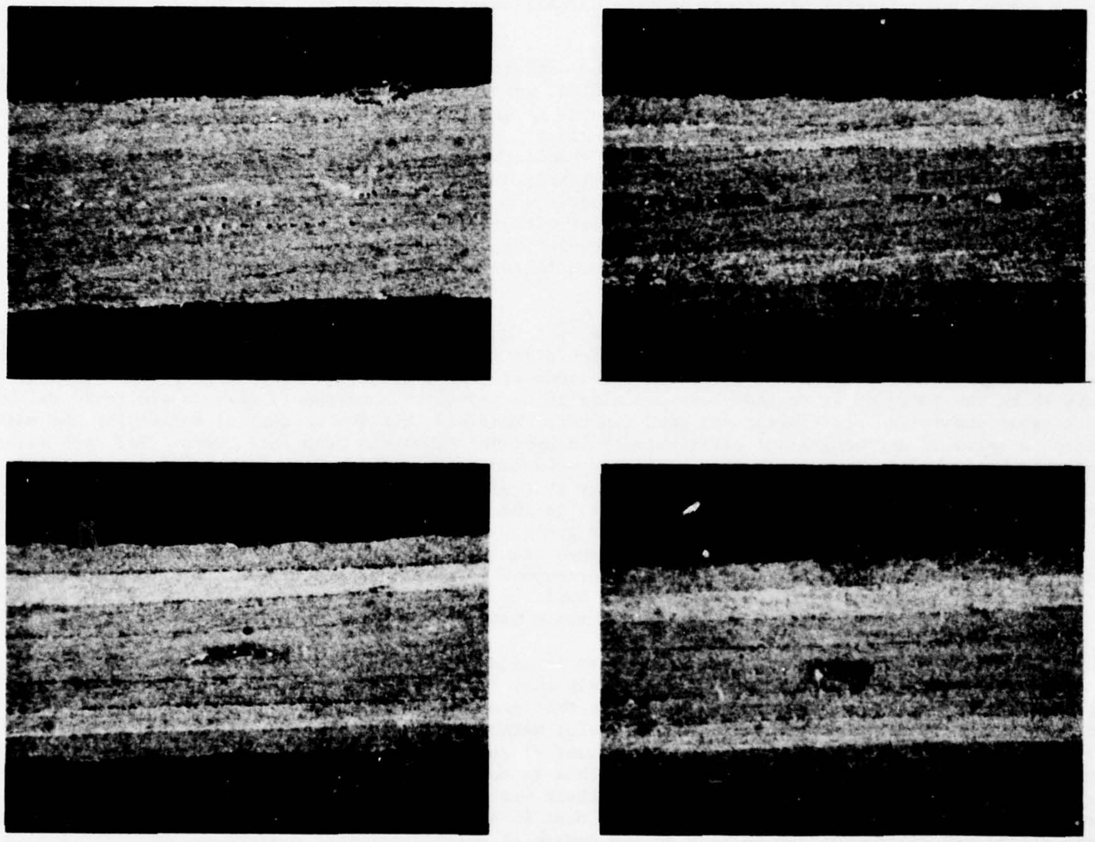
i the maximum size of delamination that is acceptable, possibly also expressing this in terms of its through thickness location and

ii the acceptable EDV.

In practice this will probably mean the imposition of some minimum overall standard together with stricter standards for defined critical or highly stressed areas. Concessions would probably be granted for small isolated areas of high EDV outside the critical regions. In fact it is likely that no completely hard and fast rules can be laid down and the importance of some anomalies will have to be resolved by discussion between the designer and the NDI unit. For example mention has not been made of side-butt defects which are readily revealed. Overlap causes a local change in thickness and a surface disturbance whilst lack of butt results in an identifiable resin rich line almost inevitably containing significant porosity. Defects such as these, or translaminar cracks induced by thermal stress, whilst obviously not desirable may still be acceptable in certain circumstances.

3.1.3 Additional NDI techniques

A large number of other techniques have been evaluated for use on composites, but for practical applications to sheet material only radiography has found widespread acceptance. Various ultrasonic



a 0.8% EDV

b 2% EDV

Fig 9 Specimens may have different microstructures but exhibit the same EDV. Two examples taken from an 8 ply CFRP panel 1 mm thick

resonance devices have been employed with varying degrees of success to find delaminations, and optical holography can reveal various anomalies, but these techniques do not appear to offer any great advantage. High frequency eddy current techniques can be used to give a good measure of the local volume fraction on unidirectional material, but they have not been found to be so reliable on angle ply laminates[24].

Radiography provides an excellent means of detecting foreign inclusions such as swarf or cigarette ash, which from time to time find their way into composites (although such inclusions do not appear to have much effect on the static mechanical properties) and it will usually find translaminar cracks. Whilst it can reveal porosity it is by no means so sensitive as ultrasonic inspection and cannot really be regarded as a quantitative technique in this respect. Its biggest advantage is probably when used with pre-preg sheets containing tracer fibres; these are usually filaments of lead glass but coated boron fibre have also been used. The extra density of the tracers makes them stand out against the background. Not only do these have the obvious advantage of revealing the lay-up directions, fibre buckling, and the inclusion of any illegal end butts between plies, but the use of a combination of oblique shots also allows the lay-up order to readily be determined. Stereo radiography can also assist here. Fig 10 shows an example of the use of tracer fibres. Microfocus radiography can be of assistance in further investigating suspect areas. Various attempts have been made to enhance the contrast of defects such as voids or cracks by the use of radio-opaque penetrants but this remains essentially a laboratory technique.

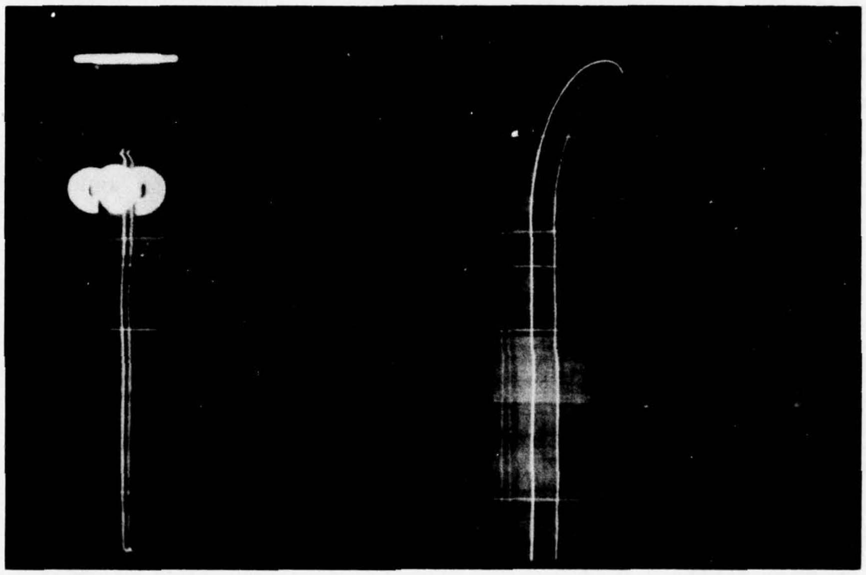
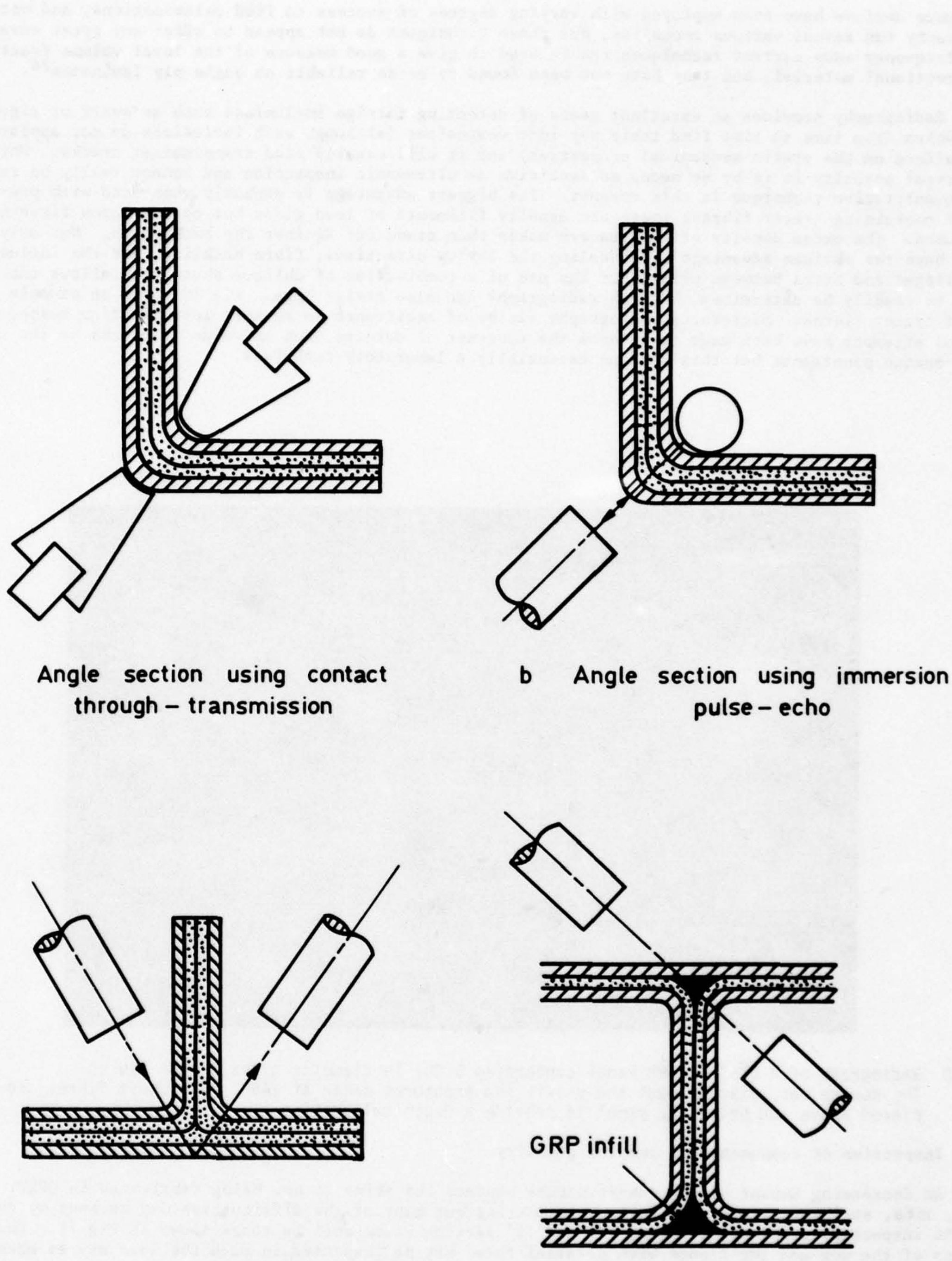


Fig 10 Radiograph of a 0^{o}-90^{o} CFRP Panel containing 0.001 in diameter glass tracer fibres. The source was rotated about the y-axis and exposures taken at $\pm 45^{o}$. The short fibres are strands placed above and below the panel to provide a depth calibration.

3.2 Inspection of components of complex geometry

An increasing amount of the sub-structure beneath the skins is now being fabricated in CFRP. These spars, ribs, stringers etc are of various geometries but many of the difficulties may be seen by considering the inspection problems of angle, 'T' and 'I' section beams such as those shown in Fig 11. Those regions of the web and the flange with parallel faces may be inspected in much the same way as sheet material, although special scanning jigs may be required. Unfortunately however, the regions in which the stresses are most complex and difficult to predict, and those which are most likely to have defects induced in them during fabrication, are those at the radii and these are of course also the most difficult regions to inspect. If the quality of the surface is sufficiently good then it is clearly possible to use a narrow ultrasonic beam, either in through transmission or using a suitably shaped reflector, as shown on the angle section in Fig 11a and b. The situation is very similar for a 'T' section but the wave meets the rear surface at an oblique angle and the resultant angle of refraction will depend on the acoustic impedance of the composite; it may therefore be better to consider trying to inspect the whole region using the beam reflected off the back wall as shown in Fig 11c.

An 'I' section beam may be fabricated in a number of ways and the inspectability depends on the details of the fabrication process and the number of stages that this involves. One method for example is to fabricate as a pair of back-to-back channels and then to bond on rectangular cross-section cover plates to reinforce the flanges (Fig 11d). It is usual to fill the cusp shaped area with GRP and inspection of the complete assembly is therefore difficult. If, however, inspection is carried out before the GRP and cover plates are added then the problem is much the same as that of an angle section. There is however, little evidence available on the efficacy of these ultrasonic techniques. At present the only practicable alternative, and one which must be employed with poor surface textures, appears to be radiography. Some of the more exotic techniques may well be worthwhile considering for applications such as this. For GRP



a Angle section using contact through – transmission

b Angle section using immersion pulse – echo

c The use of back-wall echo on a Tee section

d Practical fabrication procedures cause difficulties as on this I section

Fig 11 Ultrasonic inspection procedures required for more complex geometries

components for example the corona discharge technique[25], which reveals the local breakdown of the dielectric at voids would seem likely to be less sensitive to the various geometric factors.

Filament winding or tape winding techniques are frequently used to make components in the form of tubes or pressure vessels and once again if the quality of the surface is satisfactory there is no reason why ultrasonic techniques should not be devised. Unfortunately especially with filament winding, the surfaces of many practical components are not of a sufficiently high standard. Sometimes a cosmetic coating of resin is added and this permits meaningful attenuation readings to be taken but care must be taken in the subsequent interpretation. Components of this type however readily lend themselves to internal pressurisation and defects are often revealed as anomalies in the surface strain or normal displacement patterns. Holographic techniques provide a very convenient way of displaying the deformation patterns and revealing the anomalies. The pressurisation may be of quite a low level especially applied for NDI purposes or it may be used as part of a proof testing procedure. An example of the former is shown in Fig 12.

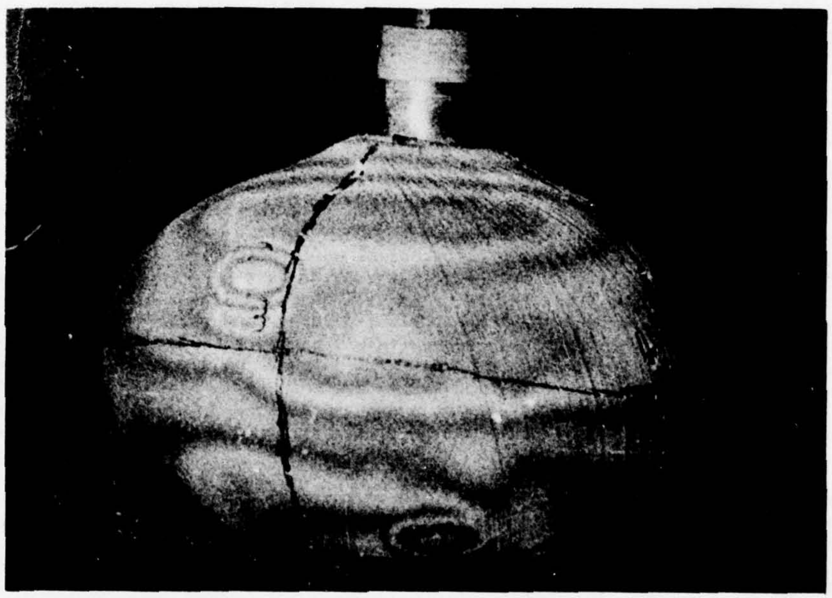


Fig 12 Holography used on a filament wound GRP pressure vessel

3.3 Inspection of adhesive bonded joints and sandwich panels

A great deal has been written on the NDI of adhesive bonded metal-to-metal joints and the following comments are only a brief summary intended to put the situation for joints with composite adherends into context.

All the devices developed for inspecting assembled bonded joints respond to -

i the presence or absence of an adhesive bond or

ii those properties of the adhesive layer which affect the cohesive strength.

No commercial instrument gives information on the adhesive strength. This is largely ensured by stringent quality control although the Fokker contamination tester[26] has proved very valuable as a laboratory tool. There is however some hope that ultrasonic frequency analysis may provide useful information on the interface characteristics[27]. The various commercial bond testers use different approaches but all of them induce various resonances into the adherends and reveal changes in the thickness, stiffness or density (including porosity) of the adhesive layer which may be related to the cohesive strength. A similar approach has been adopted for honeycomb and other sandwich panels and relationships have been derived between, for example, the Fokker Bond Tester B Scale indication and the flatwise tensile strength of such a panel. Thermal and holographic methods have also proved useful for inspecting quite large areas.

There is much less information available on the performance of these devices on joints or panels with adherends manufactured from composite materials. With reference to the various categories of defect listed in section 2.2 some general comments may however be made.

1 Many of the faults in adherend geometry are best detected by radiography although the resonance bond testers or ultrasonic inspection may also be of assistance.

2 The Fokker contamination tester was developed for metallic materials and is not applicable to composites. At present there is no real alternative to stringent quality control.

3 & 4 The absence of adhesive is detectable in many ways but those which have principally been used in the UK are -

i contact or immersion ultrasonics,

ii the Fokker bond tester (FBT)

iii the acoustic flaw detector (AFD), this has the advantage of not requiring a couplant.

Radiography may also be used in many cases and it is especially useful for detecting small gaps or porosity.

The bond testers will also respond to the thickness or condition of the adhesive bond. Careful calibration is required, however, to take into account the thickness and properties of the composite adherend, and variable quality skin material can cause considerable confusion. The author has been unable to find any published data relating the bond tester results to mechanical properties for such components.

Holography has proved to be particularly valuable for honeycomb panels with CFRP skins and a number of different types of faults have been revealed as anomalies in the fringe patterns induced by mild stressing. Interpretation of these anomalies is however not straightforward but experience gained on a limited number of components has demonstrated the sensitivity of the technique. The technique depends on the deformation of the skins to reveal sub-surface anomalies and it is therefore less successful on components having thicker skins (>2 mm). Thermal methods have also been used and photochromic paints or scanning infra-red systems[28] offer a useful technique for the inspection of large areas. Finally, although it is a point by point technique, mention should be made of the fact that the AFD has proved very successful in detecting and identifying a number of different types of flaw in a large radome having GRP skins and a foam core.

3.4 Service and environmental damage

Quite a large number of the in-service damage problems, such as impact damage, bird strikes or accidental overload, result in delaminations, cracking and bond failures and the means of detecting such defects have already been discussed. The practical problems which arise are in general those of adapting the technique for *in situ* use on the aircraft. Many of the ultrasonic procedures for example can be applied but they require some ingenuity in the use of special scanning jigs and coupling procedures. Similarly the application of holography will probably require the use of pulsed lasers. There are, however, two special in-service problems which have no equivalent at the fabrication stage; these are fatigue damage and moisture ingress both into the composite and into adhesive bonded joints. Mention should perhaps also be made of the fact that there is a potential galvanic corrosion problem in many aluminium and steel alloys when they are coupled to CFRP in the presence of an electrolyte. This has not caused many practical problems to date but the current move towards riveted fasteners could introduce problems in this area.

The response of composite materials to a fatigue environment is a complicated story and depends on the lay-up employed and the nature of the applied stress field. Unidirectional CFRP, for example shows a high level of resistance to fatigue damage when subjected to tensile loading along the fibre direction but in shear the fatigue effects are severe and significant creep is induced. With angle ply material the presence of fatigue damage is not always accompanied by a loss of strength[29] and there is really no universal criterion by means of which the degree of fatigue damage can be specified. It is in fact possible for some damage to be beneficial and it has been shown[30] that the notch sensitivity of $0\ \pm 45^{\circ}$ CFRP, which is severe under monotonic loading, is much reduced in fatigue because of the occurrence of cracking which reduces the sensitivity to the stress raiser. Thus although internal damage can be detected by such techniques as ultrasonic attenuation or high frequency eddy currents care must be taken in the interpretation of such data. Nonetheless ultrasonic attenuation has been used as a monitor of fatigue damage.

Measurements of the shear modulus and of the damping coefficient in torsion have been used[31] to detect damage in CFRP rods and it was found that the latter was a much more sensitive indicator. A comprehensive investigation on the early detection of fatigue damage is reported by Salkind[32]; this was principally performed on GRP tubes but some unidirectional CFRP was also tested under complex combinations of bending and torsion. Torsional stiffness was found to be the most useful indicator of damage and a three stage process was identified. The stiffness measured was however the overall stiffness of the laboratory test specimens and no attempt was made to take a local measure of stiffness such as might perhaps be given by the ultrasonic shear wave velocity. Temperature sensitive coatings revealed hot spots indicating local damage and holography was used to monitor the growth of damage. The presence of hot spots has also been established[7] for CFRP under flexural fatigue but the opacity of the material to infra-red radiation prevented their non-destructive detection.

It would appear therefore that NDI is not yet offering enough in this field but that development of suitable techniques is still hampered by a lack of understanding of the exact mechanisms involved. It is in fact desirable that NDI procedures should be more closely integrated with the fatigue test programmes.

Despite the importance of detecting and quantifying the degree of moisture ingress together with any resultant damage there is little information available on suitable NDI procedures. There is, however, a useful paper by Kaelble[33] which describes a current research programme and concludes that for CFRP the translaminar ultrasonic velocity and attenuation give a measure of the moisture content and strength degradation respectively. Thermography and penetrants are suggested for detecting the failure of protective surface treatments. He suggests also that gauges such as strain density sensors or dielectrometer electrodes could be fabricated into components to monitor the internal stresses induced by moisture ingress. Microwave or infra-red spectroscopy are proposed as a means of analysing the state of the

chemical structure of the composite surface. Some of the more exotic techniques such as nuclear resonance or neutron gauging may also be able to contribute.

4 THE USE OF ACOUSTIC EMISSION TECHNIQUES

Although not strictly a non-destructive technique acoustic emission (AE) can nonetheless play a very useful role closely related to that of NDI by revealing what is happening in a mechanical test. As soon as stress is applied to a CFRP component minor failures will occur at local points of weakness resulting in the emission of small stress waves. By the use of suitable instrumentation these waves may be detected, counted and processed. It is not yet possible unambiguously to characterise individual failure events, especially in a structural configuration[34], but recent developments make this objective increasingly feasible. In the meantime however an examination of the amplitude distribution of the signals has proved very useful and two examples will be briefly described.

A block diagram of the instrumentation employed by the author is shown in Fig 13. The amplitude sorter consists of a pre-amplifier followed by three amplifier stages each having a gain of 20 dB (× 10); four fixed level trigger units are provided as shown so that the signals are categorized as falling into one of four amplitude ranges the most sensitive level being designated Level 1, the next Level 2 and so on. Each time that a given trigger is activated a pulse is stored on the corresponding channel of a magnetic tape recorder. On replay the cumulative count on each channel is displayed, using an appropriate scaling factor, on an X-Y plotter.

Consider first the results of tensile tests on two different quality samples of unidirectional CFRP. The ends of the specimen had been electroded and the changes in resistance were monitored to give a measure of fibre breakage; the initial decrease in resistance is attributed to transverse compression caused by the wedge grips. It should be noted that the AE cumulative counts are displayed on a weighted presentation, there being ten times more counts per division for Level 1 than for Level 2 and so on.

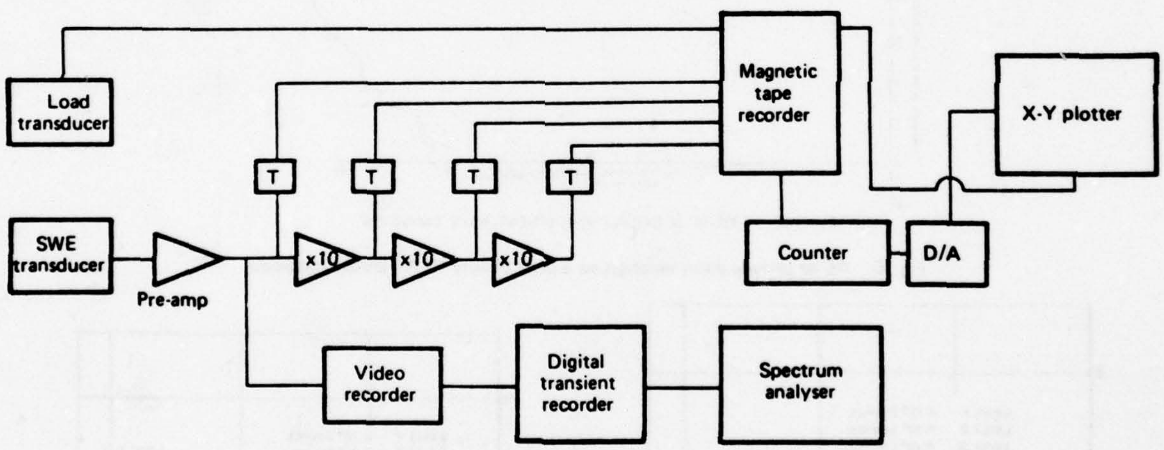


Fig 13 Block diagram of the acoustic emission equipment

The results obtained on a good quality specimen are shown in Fig 14 and it can be seen that after the initial slight decrease in resistance referred to above there is only an increase in resistance just before final failure. Examination of the cumulative count curves shows that this point, which is the onset of significant fibre breakage, is also revealed by counts at the high amplitude Levels 3 and 4. The lower amplitude emissions at Levels 1 and 2 are therefore assumed to emanate from lower energy events such as matrix cracking and interface failure. It is perhaps interesting to note that good quality specimens of this type exhibit a pronounced 'Kaiser effect'[35] indicating that the emissions arise from irreversible failure events. This result should be contrasted with the results of an identical test on a poor quality specimen shown in Fig 15. Here there is a significant decrease in resistance caused by the transverse compressions and fibre fracture starts well before final failure. Noting that there is a 20:1 change in scale for the cumulative count curves it can be seen that prior to this point the counts at Levels 1 and 2 are much the same for both specimens. Once fibre fracture has started, however, there is a large number of counts at all levels building up to final failure.

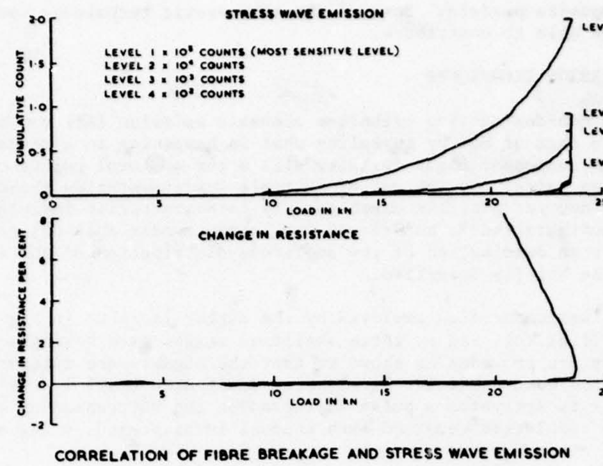


Fig 14 AE amplitude discrimination on a good quality CFRP tensile specimen

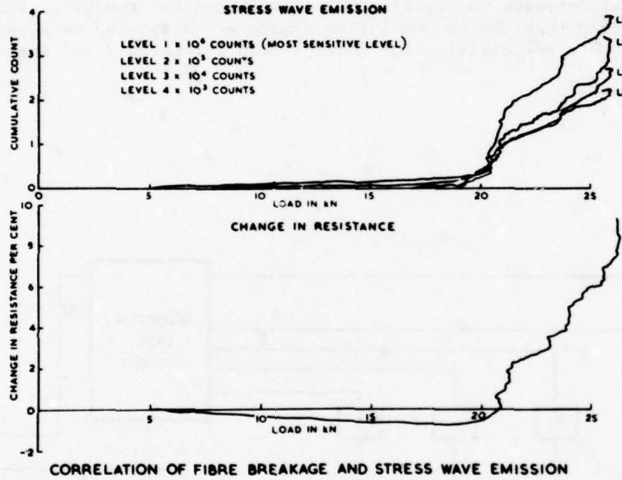


Fig 15 AE amplitude discrimination on a poor quality CFRP tensile specimen

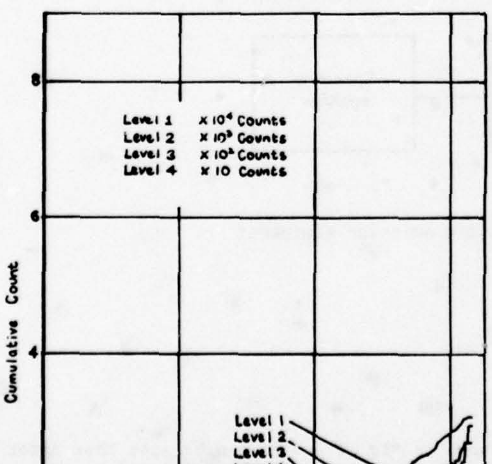


Fig 16 AE amplitude data from a bending test on a small CFRP structural component of good quality

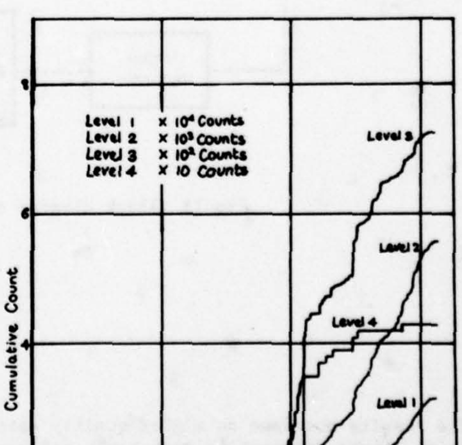


Fig 17 AE amplitude data from a bending test on a small CFRP structural component of poor quality

Acoustic emission can also add considerably to the value of a proof test and here again examination of the amplitude distributions can be most revealing. Fig 16 shows the results of a proof bending test on a small structural component; a weighted presentation has again been used and the curves for the four levels lie fairly close together. This was typical of good quality components although they did not always lie in order as shown. There is a marked difference for poor quality specimens; these were much more variable but typical results are shown in Fig 17. Two factors should be noted. First the predominance of high amplitude counts and second the fact that the counts at Level 1, the most sensitive level, are much the same as those obtained on the good quality component. Thus AE measurements taken in the conventional way using the highest sensitivity available would not have revealed this difference in emission characteristics. Both components successfully sustained the proof load with no obvious signs of damage and without acoustic emission there was no way of predicting the final performance.

Acoustic emission should really be considered as a technique which is complementary to the true NDI techniques discussed earlier. Used with care it can reveal whether or not failures have occurred during a structural test, and it is sometimes possible to use location or zone discrimination techniques to say where this event occurred. Only limited information is at present deducible about the nature of the event but by telling the inspector when - and perhaps where - to look it can offer considerable assistance to conventional NDI. Periodic proof testing is not feasible for many components but in the cases when this can be done AE offers the possibility of detecting in-service damage.

5 DISCUSSION AND CONCLUSIONS

The development of NDI techniques for composites, and indeed the development of the composites themselves, is hampered by a lack of knowledge on the significance of defects. Close liaison between the fabricators and the NDI team is essential for not only does it give the rapid feed-back of information required in order to optimise the fabrication process, but it also ensures that the NDI team has access to representative defective specimens that can be examined destructively after NDI. This liaison is not only required during the development of fabrication procedures but also during the routine production of material for mechanical test specimens. Many of the difficulties initially encountered with composites arose from variability in the material and a greater involvement of NDI might well have obviated much of this. Additionally there is a need for the production or selection of defective material so that the effects of various defects on the structural performance may be studied. Only when this information is available can meaningful acceptance standards be specified.

In summary the application of NDI to sheet material is proving adequate although undoubtedly there is a good deal more information that could be extracted. Components of more complex geometries do raise additional problems and there is clearly room for improvement here. The more advanced fabrication procedures in which several elements are cured at the same time are certain to make NDI more difficult and on occasions they will make it almost impossible using the currently available techniques. The other major problem areas which should be highlighted are:

1 The prediction of the strength of adhesive bonds and the monitoring of environmental degradation. This is a general structural problem but it is further complicated if the adherends are composite materials.

2 Detection of in-service damage, especially moisture ingress.

ACKNOWLEDGMENT

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THE RESONANCE-IMPEDANCE METHOD AS A MEANS FOR QUALITY CONTROL OF ADVANCED FIBRE REINFORCED PLASTIC STRUCTURES

by

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SUMMARY

The resonance frequency/impedance method, that has shown during twenty years to be effective for structural adhesive bonded joints, appears to be also promising for inspection of advanced composite structures laminates as well as bonded joints. The principles of testing are discussed, as well as practical applications in recent advanced composite structures development programs.

INTRODUCTION

The availability of advanced fibre reinforced plastic materials for structural applications has given the designer of such structures an entirely new dimension to his work. He, not any more selects materials for application in his structures, but now he has the possibility to "design" composite materials most suited for use in the structure concerned. Parameters such as:

. fibre volume fraction
. fibre orientation
. lamination configuration
. matrix resin

offer ample possibilities for variation within the requirement field for structural application of advanced fibre composites. Each individual combination of these parameters offers a material with a distinct set of mechanical properties. It is certainly not the intention of this paper to make propaganda for an, as wide as possible variation of the available parameters, instead of making a plea for more standardization of laminate configurations. However, the mentioned parameters will be present. The consequence of these variations available to the designer of composite structures is, that he requires the manufacturing organization to guarantee him that those parameters in the actual structure hardware will have the values that he considered to be desirable as a basis for his design.
In view of the close dependancy of many of such parameters with the applied manufacturing processes much emphasize has to be placed on the quality control activity. In-process control plays an important rôle for the realization of the desired properties of the endproduct. A complete answer, however, cannot be given in this way. As destructive sample testing and proofloading are by no means popular methods for assessment of composite structure qualities, non-destructive inspection unavoidably must play an important rôle. The effectivities of the generally accepted means of N.D.I. have been described in detail in many papers, and publications, some of which are mentioned in the added reference list.

The intention of this paper is to discuss the merits and limitations of an N.D.I.-method, that has seen large scale use only in a rather limited field of application: that of the quality control of adhesive bonded joints both between metallic or non-metallic components. This method is the resonance-impedance method that saw world-wide application in the Fokker Bond Tester System.

In recent years there are indications of quite successful use for quality control of important advanced composite structural components, not only in the adhesive bonded joints there off but also of the laminates themselves. In the following the principles of resonance impedance inspection of composites is discussed, as well as some practical applications.

QUALITY VARIABLES OF COMPOSITE LAMINATES

As mentioned in the introduction the composite materials can be varied according to the intention of the designer. However, also variations can be introduced by variations in the manufacturing processes. Deviations from the specified fibre volume fraction, fibre orientation lamination configuration and matrix properties can be introduced by variations in:

. lay-up
. local curing pressure
. local resin bleeding
. curing temperature and -time

Most important quality variations show up as:

. laminate thickness variations
. matrix density variations (porosity)
. delaminations

PRINCIPLE OF RESONANCE IMPEDANCE TESTING

Determination of mechanical properties of cured adhesive resin layers between bonded objects by means of resonance testing dates back to the work of Bordoni, Dietz and co-workers.[1,2] They measured the dynamic moduli of resinous layers bonded between solid metal cylinders at ultrasonic frequencies. Fig. 1 shows the principles of this method.

Early attempts to apply this valuable principle on actually adhesive bonded sheet-metal structures were seriously hampered by the fact that the thickness resonance frequencies experienced within one component covered such a very wide range due to the many variations in metal-thicknesses as used in such bonded structures. In the effort to develop a universally applicable instrumentation for such a purpose the principle was developed not to measure the resonance frequency of the bonded combinations themselves but to determine the changes of the resonance characteristics of a well defined body, when acoustically coupled to those bonded assemblies. In fact, the calibrated body then is coupled with a mass/spring-dashpot/mass system (figure 2). It is obvious that the resonance properties of this "reference" body will be modified by the magnitude of the coupled mass in comparison with that of the reference body in the free state and the dynamic properties of the gluelayers in between these masses.[3-12] About twenty years of use of this principle has shown its capabilities of providing quantitative quality information about the cured gluelayer between bonded layers, even in multiple laminations. In the case of inspection of fibre reinforced materials the operation principle must be somewhat different. In the adhesive bonded application the variations in the resonance characteristics are caused mainly by the variations in the gluelayer parameters: modulus, density and thickness. For a given configuration of joint the metal masses (density and sheet thickness) are constant and considered to be infinitively stiff; they are initially given factors for which the instrument can be preadjusted. The gluelayer itself is considered to act as a massless spring with variable dynamic properties. When inspecting fibre reinforced solid objects these are directly acoustically coupled to the reference body. The resonance characteris-

tics of the system can be varied now from the reference values by all parameters that can influence the mechanical properties of the laminate concerned. Figure 3 illustrates that in the latter application the coupled mass is not considered to be infinitively stiff and incorporates the spring and dashpot indicating the variability of the dynamic properties of that coupled and variable mass.

The discussed principle for testing bonded joints was brought to practical application by chosing as a reference body a piëzo-electric transducer with suitable mass and dimensions, allowing a quick and complete analysis of the resonance characteristics looked for (Fig. 4) Both the resonance frequency and the impedance are presented in directly readable form by the instrument. (Fig. 5) The correlation between the laminate properties and the resonance/impedance characteristics in the configuration of the laminate coupled with the reference body can be explained as follows:
The reference body and the laminate directly coupled with it are shown in figure 6. Regardless the fact that the laminate extends far beyond the contact area, only the laminate area equal to the contact area needs to be considered due to the high ultra sonic frequencies that are used. Experiments have shown that areas adjacent to the contact areas have little or no influence on the results. In figure 7 the basic resonance frequency f_R of the reference body with length l_R (without coupled laminate) is:

$$f_R = \frac{C_R}{2\, l_R}$$

in which C_R is the ultrasonic longitudinal wave velocity. The resonance frequency f_C of the coupled system of reference body and laminate is:

$$f_C = \frac{C_C}{2\, l_C}$$

in which C_C = apparent resultant wave velocity of the coupled system, l_L being the laminate thickness

$$l_C = l_R + l_L$$

A longitudonal wave travelling from one outerface of the coupled body to the other outerface uses a time:

$$\text{of} \quad \frac{l_R}{C_R} + \frac{l_L}{C_L} \quad \text{seconds,}$$

C_L being the wave velocity in the thickness direction of the laminate. The resultant apparent wave velocity C_C for the system of the coupled bodies can be expressed as:

$$C_C = \frac{l_R + l_L}{\frac{l_R}{C_R} + \frac{l_L}{C_L}}$$

The basic resonance frequency of the coupled system is then:

$$f_{R_o} = \frac{1}{2} \cdot \frac{C_R \cdot C_L}{l_R \cdot C_L + l_L \cdot C_R}$$

During the further discussion it will appear that also the higher harmonics may play an important rôle. The factor $\frac{1}{2}$ then must be replaced by $\frac{3}{4}$; 1 etc. multiplying f_R with respectively a factor 1,5; 2,0 etc. The above is particularly valid when the ultrasonic wave velocity of the reference body is chosen to be of the same order of magnitude as that of the fibre reinforced laminate in thickness direction.
In the following only pure longitudinal resonance is assumed to take place. However, in practise, such as in the Fokker Bond Tester also other forms of resonance are used in the various probes.

INFLUENCE OF LAMINATE VARIABLES

(a) Laminate thickness

In the case of laminate thickness variations only l_L is variable and all other resonance frequency influencing parameters are kept constant. Martin[13] and others found the ultra sonic wave velocity for void free carbon laminate with 70% fibre (volume) content to be $3{,}5 \cdot 10^5$ m/sec. Using a reference body with a thickness of 0,635 cm and a resonance frequency of $290 \cdot 10^3$ Hz the value of $C_R = 3{,}68 \times 10^5$ cm/sec. Table 8 and diagram 9 show the laminate thickness influence on the basic and first harmonic resonance frequencies. The resonance frequencies of the reference body alone are also indicated. It appears that there will be considerable shifts in resonance frequencies relative to that of the reference body alone. The question is obvious whether the presence of more than one resonance mode will not be disturbing. In practical inspection this phenomenon is just of great help, similar as has been experienced in testing bonded joints. It allows to use only a limited range on the frequency scale due to the fact that when the basic mode runs out of the scale the second mode comes within working range. The mode change is clearly indicated by a strong variation in the impedance, that can be read from the proper indicator. Reference bodies with different dimensions, mass and resultant resonance frequencies allow an optimum selection of typical configurations to be tested. (Fig. 10).

(b) Void detection

For quality control purposes actual thickness measurement on the total laminate will be carried out only by this method on a limited scale when other, easier, means will fail p.e. due to lack of accessibility. However, the described phenomenon is used effectively for determination of interlaminar voids. The method provides straightforward means for measuring not only the void dimensions, but also its distance in thickness direction below the laminate surface. Voids show up immediatedly as a distinct frequency shift in a similar way as a sharp change in laminate thickness does. Fig. 11. The fact that the part of the laminate that is resonating with the reference body is equal or even smaller than the contact area creates an excellent sensitivity of the inspection. Laminates upto 4 mm thickness can be inspected with a reference body of 0,95 cm diameter that will detect effectively interlaminar voids of that diameter or even much smaller. Using a well balanced ratio between reference body diameter and thickness and between the latter and the laminate thickness advanced composite laminates of the largest practically applied thicknesses can be inspected, on voids with remarkable sensitivity.

(c) Density variations

Laminate density may be varied due to changes in fibre content and/or air enclosures, porosities. The influence of the fibre content and the void content on the resonance properties can be readily understood from the fact that:
the ultrasonic wave velocity perpendicular to the laminate plane is:

$$C_L = \left[\frac{E_L}{\rho_L}\right]^{\frac{1}{2}}$$

in which: E_L = modulus of elasticity of laminate in thickness direction.
ρ_L = density of laminate

Various sources have published extensive test results on the influence of void-content on both modulus, density and the resultant change in wave velocity. Martin found wave velocity changes between 2,7 and $3{,}4 \cdot 10^5$ cm/sec. for volume fraction variations between 50 and 75% and void contents between 0 and 4%. These changes are mainly caused by the void content and only insignificantly by the fibre content.[13-17]

The influence of changes in wave velocity over a range of 2,25 to 3,5 . 10^5 cm/sec. on the resonance frequency of a 2 mm thick CFRP laminate using the same reference body is shown in table 12. This particular range is that between ideal void free and the fully rejectable quality of 5% porosity; an acceptable quality having a void content of 2% or less. There is a very distinct difference in resonance frequency shift between those of medium and high and too low quality. In practical testing such a range of 36 kHz means a larger part of the indicator range used with the particular instrument adjustment. Adjustments between 1,2 and 120 kHz for the complete indicator width can be made by just turning a switch.

APPLICATION PRACTISE

When using during manufacture autoclave or vacuum/oven curing methods with single sided open, moulds, very often increasing void content coincides with some increase of the laminate thickness for a given number of prepreg plies. Both variables having similar effects on the resonance frequency of the system the sensitivity for anomalies in the laminate is increased. In the case of complicated composite structures to be inspected, having considerably different configurations from point to point, it is effective to use reference standards showing the acceptable laminate quality for each important configuration. Otherwise the Fokker Bond Tester correlation diagrams are used in which for each probe (reference body) the influences of laminate thickness and void content are indicated. Figure 13 shows a typical example of such a diagram. It should be noted that the diagram has an unusual feature of indicating the increasing resonance frequency from left to right. This is an historical feature based on the fact that from the beginning the Fokker Bond Tester A-scale (frequency) indicator showed frequency increases as lefthand shifts and -decreases as righthand shifts. Furthermore it is practise not to use the actual resonance/frequency of the system but to express the quality variations as shifts in frequency relative to the reference body resonance frequency in Left (higher) or Right (lower) shifts.

In figure 14 a series of ultrasonic C-scan pictures is given of a typical experimental production panel. The pictures are given at various reception dB-levels. In order to exclude any thickness influences and to study the void content effect separatedly the specimen was machined to a thickness of 3,0 mm before testing. The locations with the lowest attenuation at the applied 10 mHz frequency show attenuation of $2\frac{dB}{mm}$ or less, which according to Stone[16] indicates a void content of $\leqslant$ 1%. In the centre of the panel there is an area that shows attenuation of in the order of $5{,}3\ \frac{dB}{mm}$ indicating void contents of 2,3% or higher; anyway a level that generally is considered to be unacceptable. The same panel inspected along the resonance (impedance) method by means of the Fokker Bond Tester with probe No. 3814 and a 290 kHz resonance frequency showed in the low void content areas ($\leqslant$ 2%) resonance frequencies at 298 kHz and in the higher void content area ($\geqslant$ 2,3%) 289 to 291 kHz. In figure 15 the frequency shifts from the reference frequency of 290 kHz are indicated. Also the B-scale values indicating the impedance are shown as well. A value of B = 100 is obtained with the transducer in free air and at 290 kHz. Frequency shifts of the indicated magnitudes are with proper instrument adjustment readily detectable.

INSPECTION OF ADHESIVE BONDED JOINTS BETWEEN COMPOSITE PARTS

The application of the resonance method on adhesive bonded joints in advanced composite structures can be done similarly to the established practise for metal bonded joints. The sensitivity of the method in this case is even better. Thanks to the relatively high moduli and low masses in comparison with aluminium alloys the applicability of the given

reference bodies (probes) obtains a larger sheet thickness range.[18]

APPLICATION EXPERIENCE

It is quite understandable that at Fokker-VFW the Fokker Bond Tester was applied from the earliest moment of C.F.R.P. research and development. Figure 16. This was done in conjunction with other N.D.I. methods such as ultra sonic pulse echo and throughtransmission as well as interference holography.[19] Most experience, however, has been accumulated by the companies that have been favoured with much larger scale advanced composite hardware programs. Grumman Aerospace Corporation used the method all through the production of large structural advanced components of the F-14 Tomcat jetfighter, leading to the most impressive experimental production of the advanced composite stabilizer for the B-1 bomber.[20] Figure 17. According to Dastin of Grumman for that structure the resonance technique with help of the Fokker Bond Tester is used in conjunction with ultra-sonic throughtransmission and pulse echo techniques. The resonance method is applied effectively for detailed analysis of void areas that have been discovered initially by faster scanning techniques. Representative standards, covering a range from 3-100 plies are used in order to assist with determination of the depth location of a detected anomaly in a laminate. Also adhesive bonded joints between advanced composite elements and metal components were inspected with the Fokker Bond Tester. Hagemaier of the Mc Donnell Douglas Corporation[21] reports that also in conjunction with the experimental program of the advanced composite rudders of the DC-10 the resonance method is applied successfully, both for endproduct quality control and inspection after laboratory or flight tests. The resonance method is called to be basically used as a "thickness continuation" test, such as has been discussed earlier. If a delamination has occurred a thinner than normal response is obtained. The thickness response will indicate the relative depth of the delamination below the skin outer surface. If the skin has separated from a rib or spar, the response will be less thick than normal and will be equal to the total skin thickness in the local separation area. The instrument is precalibrated for thickness by employing two graphite epoxy stepwedge reference standards. One standard is 2 to 14 ply in 2 ply increments. The second standard is 16 to 34 ply in 3 ply increments.

Figure 18 has been borrowed from the relevant paper by Hagemaier for the 1976 ATA Nondestructive Testing forum.[21] It is interesting as it shows the desired frequency (A-scale) indications to be obtained by the Fokker Bond Tester on a complex detail of the DC-10 C.F.R.P. rudder. The inspection is started by adjusting the C.R.T. indication (A-scale) for the reference body resonance frequency (290 kHz) 5 kHz off centre to the left. Coupling to a 6 plies skin laminate changes the frequency to approx. 285 kHz which brings the indication in the centre of the indicator. Additional reinforcement of the basic skin laminate reduces the resonance frequency to approx. 280 kHz for 10 plies; 270 kHz for 16 plies, 265 for 20 plies and 260 kHz for 24 plies. When going to 30 plies the second mode comes into operation that shows an indication at 300 kHz. For the particular structure detail the desired frequency indications are given, taking into account that each division line on the horizontal scale equals 5 kHz shift and the center frequency is 285 kHz.

Advanced composite skins for reasons of avoiding static electricity problems and reducing lightning strike damage very often have outerplies of metal wire mesh laminated simultaneously with the fibre laminates. The resonance inspection method has shown to obtain less difficulties when inspecting laminate quality below the wire mesh and also the bond of the wire mesh with the laminate than experienced with other methods.

CONCLUSION

The resonance/impedance inspection method offers an important completion to other non-destructive methods for inspection of advanced composite structures.

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Figure 1 Method of Bordoni for resonance testing of cemented bars; Specimens geometry and dynamic model.

For: ρ = density of bar

δ = glueline thickness

ℓ = length of bar

f_0 = resonance frequency of solid bar

f_1 = resonance frequency of bonded bar

Modulus of elasticity of adhesive is:

$$E_1 = 4\rho \cdot \ell \cdot \delta \cdot f_0^{\,2} \cdot \frac{f_1}{f_0 - f_1}$$

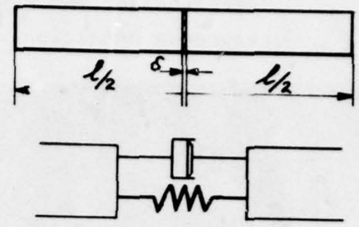


Figure 2 Dynamic model of determination of dynamic properties of adhesive bonded joint by resonance testing with help of a reference body (M_R) with calibrated resonance characteristics.

M_1 and M_2 are the bonded masses.

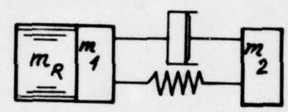
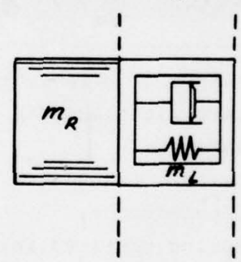


Figure 3 Dynamic model of determination of dynamic properties of laminate M_L by means of resonance testing with help of a reference body (M_R) with calibrated resonance characteristics



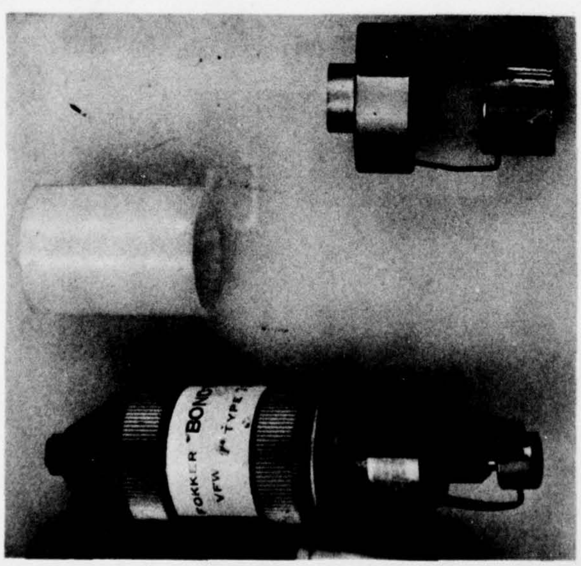
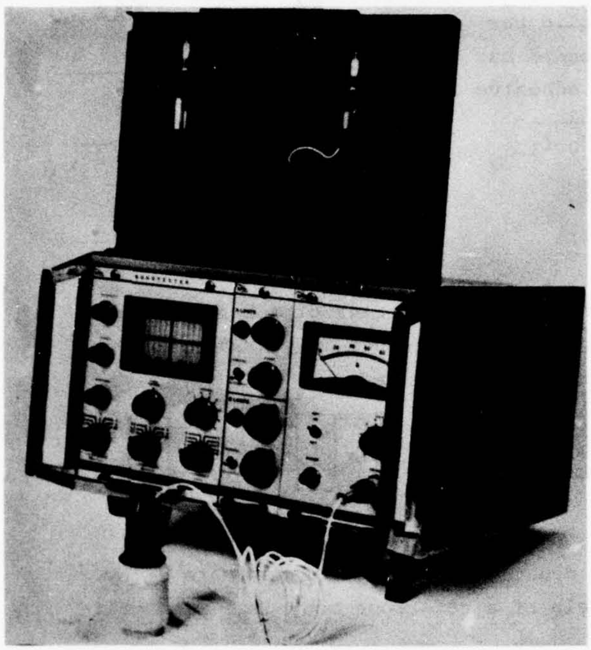


Figure 4 Probe containing piëzo electric transducer that has the function of calibrated reference body.

Figure 5 Fokker Bond Tester instrument for non-destructive inspection by means of the resonance principle.
The resonance frequency changes can be read from the cathode ray tube at the lefthandside. The other instrument indicates the relative impedance of the resonance condition.



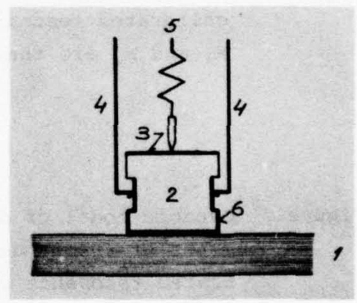


Figure 6 Principle of ceramic transducer used as a reference body, in acoustical contact with laminate (Fokker patent).

1. laminate
2. ceramic transducer (reference body)
3. topelectrode
4. spring contacts for lower electrode
5. spring contact for top electrode
6. lower electrode locally extended to the sidewall of transducer

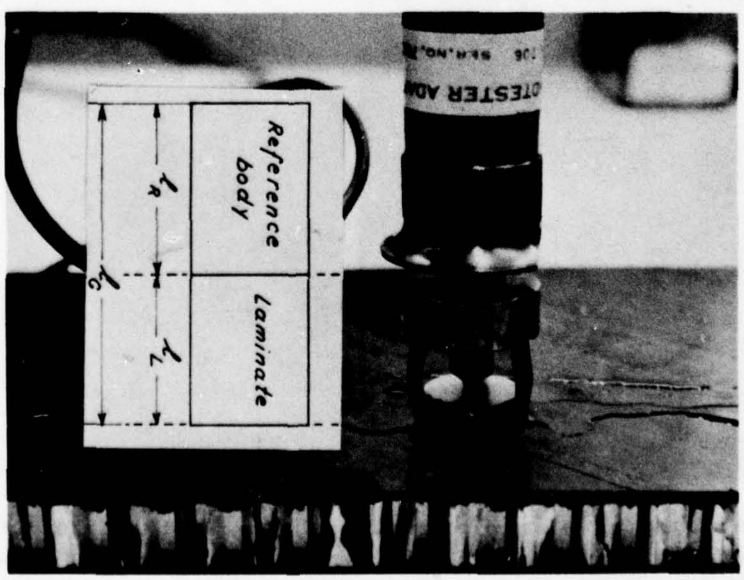


Figure 7 Reference body in contact with laminate

TABLE 8

Laminate thickness	Longitudinal Resonance frequency kHz		Resonance frequency shifts from 290 kHz	
l_L cm	basic	le harm	basic	le harm
0	290	435	0	+145
0,1	248	373	-42	+ 83
0,2	218	326	-72	+ 36
0,3	194	290	-96	0

Influence of laminate thickness on the longitudinal resonance frequency of the reference body coupled to the laminate.

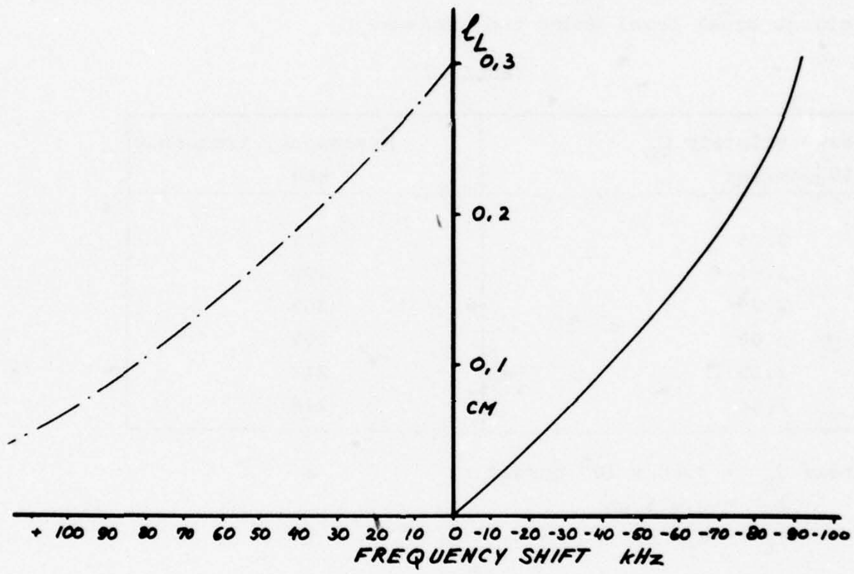


Figure 9 Results of table 8 expressed as changes of the basic longitudinal resonance frequency of the reference body.

TABLE 10

Reference body		Resonance frequency
Diameter cm	Thickness cm	kHz
3.8	2.54	89.7
3.17	2.54	97.3
2.54	2.54	86
1.9	1.27	151
1.9	0.635	367
0.635	0.635	334
0.95	0.635	290
0.95	0.95	227

Range of different reference bodies (probes) with different masses and resonance characteristics as used in practise.

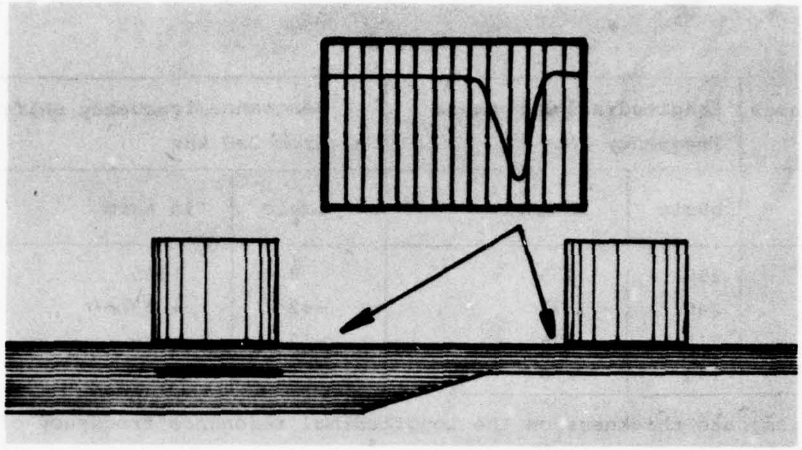


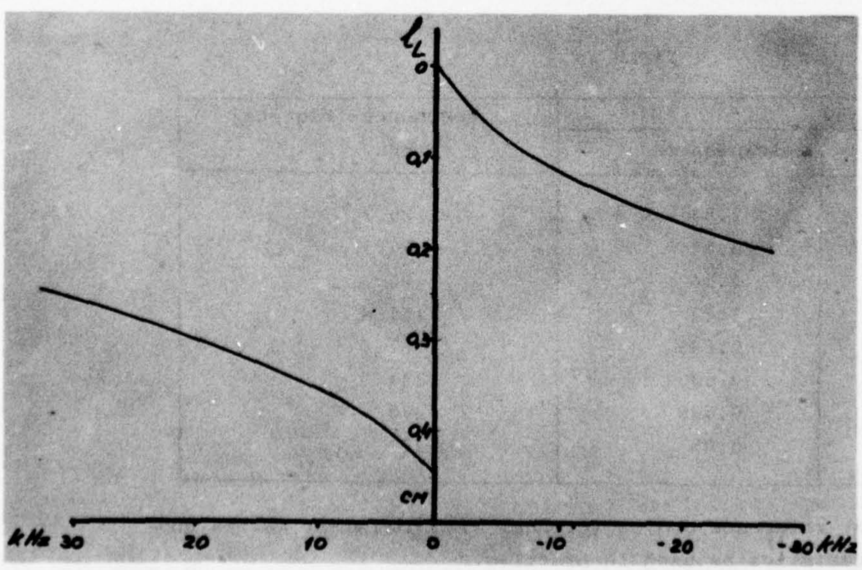
Figure 11 Change in laminate thickness has same effect on resonance peak position as void at equal level under top surface.

TABLE 12

Wave velocity C_L 10^5 cm/sec	Resonance, frequency kHz
2.25	191
2.50	198
2.75	202
3.00	209
3.25	214
3.50	218

for: C_R = 3,68 x 10^5 cm/sec
l_R = 0,635 cm
l_L = 0,2 cm

Influence of variation of wave velocity on the resonance frequency of probe on 2 mm laminate over a range between 3.5 x 10^5 cm/sec. (equal to void free) and 2.25 x 10^5 cm/sec. (equal to approx. 5% porosity).



Typical correlation diagram between laminate thickness and frequency shift for Fokker Bond Tester probe 3814. Note considerably smaller shifts due to special resonance characteristics of transducer

Figure 13

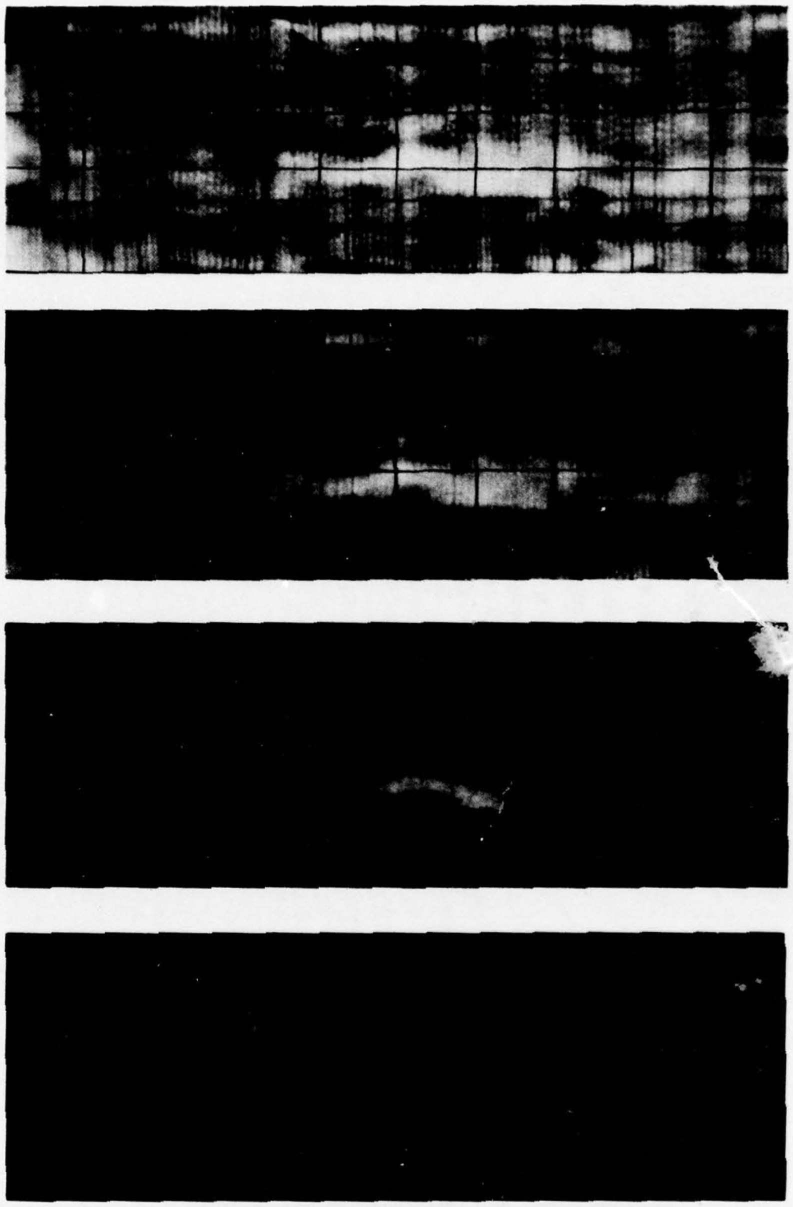


Figure 14 a, b, c, d, U.S. C-scan at 10 mHz of the same 3 mm thick carbon fibre epoxy laminate recorded at four different attenuation levels with intervals of 2/3 $\frac{dB}{mm}$ between levels.

L 7/40	L 7/40	L 6/40	L 7/40	L 6/40	L 6/40	L 6/40	L 6/40	L 6/40	L 7/40
L 7/40	L 6/40	L 6/40	L 4/40	L 5/40	L 6/40	L 2/40	L 6/40	L 6/40	L 6/40
L 7/40	L 6/40	L 5/45	L 3/50	L 6/30	L 0/65	L 1/40	L 6/45	L 6/45	L 6/40
L 8/35	L 7/40	L 6/40	L 7/40	L 6/40	L 5/40	R 1/60	L 6/45	L 6/45	L 6/45
L 9/35	L 7/40	L 6/40	L 6/45	L 6/45	L 6/50	L 6/40	L 6/45	L 6/40	L 6/45

Figure 15 Fokker Bond Tester readings with probe no. 3814 of same panel of Figure 14 showing frequency shift, from 290 kHz (L is positive; R is negative). Second figure is relative impedance.

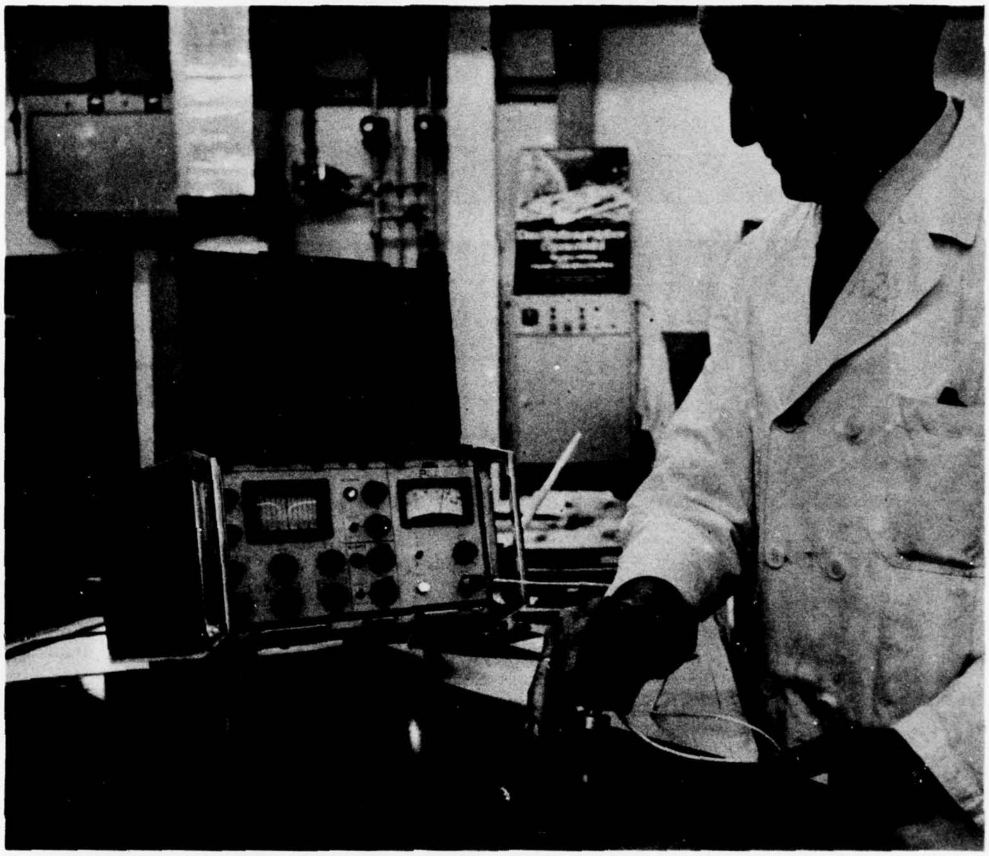


Figure 16 Fokker Bond Tester in use for inspection of experimental carbon fibre - epoxy component for Fokker F-28 "Fellowship".

Figure 17a Large graphite-epoxy skin laminate for B-1 stabilizer in which the resonance method has been applied extensively for analysis of voids in particular on depth location. (Courtesy Grumman Aerospace Corp.)

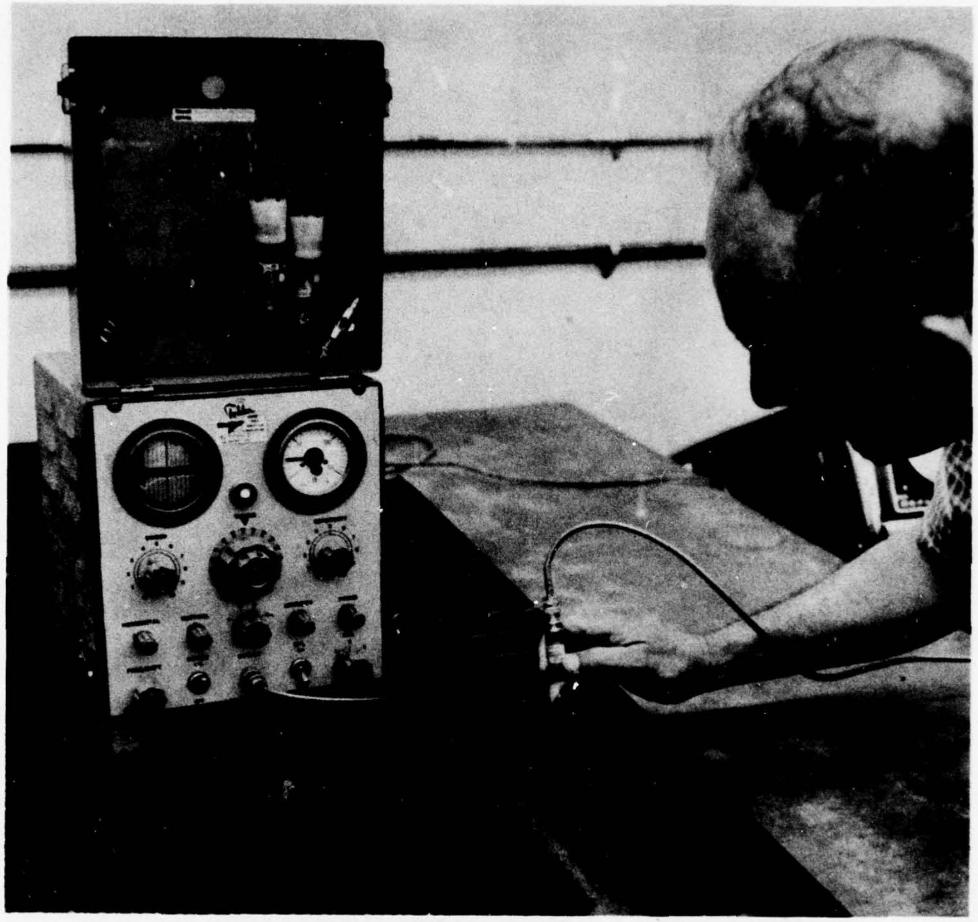


Figure 17 b. B-1 graphite/epoxy sine wave spar inspected for delaminations or voids by Fokker Bond Tester (Courtesy Grumman Aerospace Corporation)

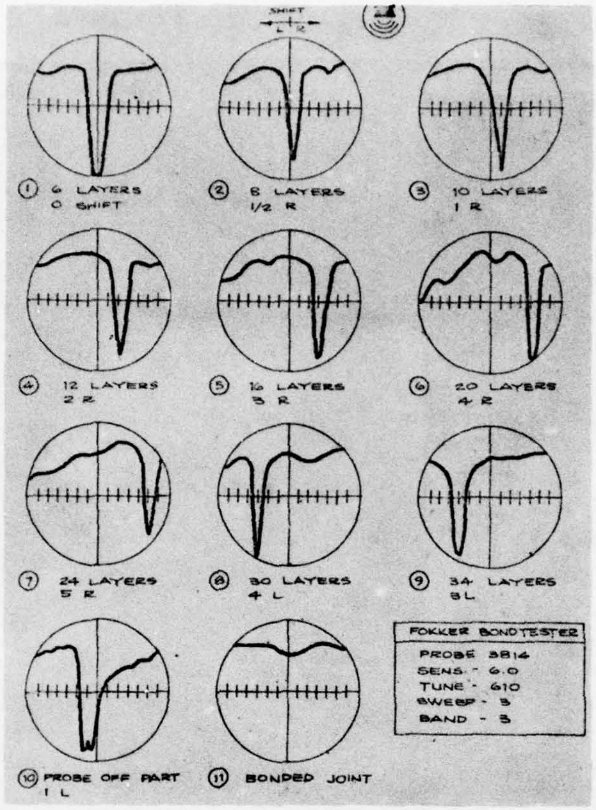


Figure 18 a. Resonance frequency peak position on the Fokker Bond Tester A-scale for the probe (reference body) in contact with various numbers of plies.

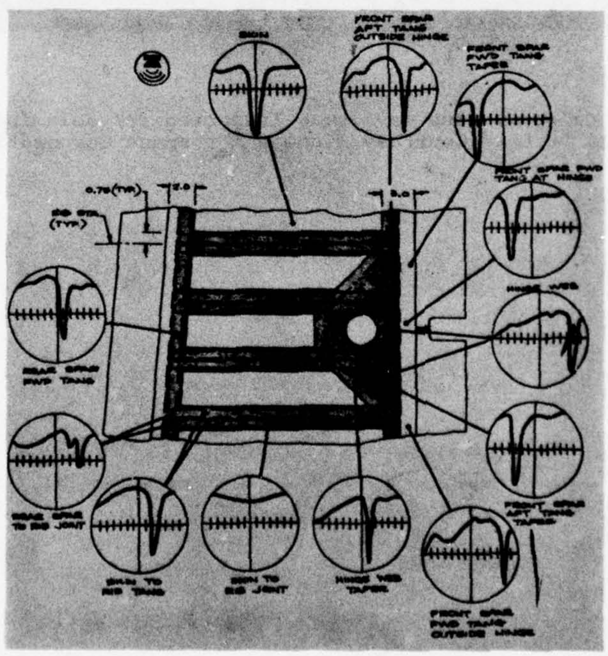


Figure 18 b. Typical frequency peak positions to be obtained on a detail of the Douglas DC-10 graphite epoxy rudder (courtesy McDonnell Douglas Corp.)

INSPECTION OF CARBON FIBRE PARTS AFTER FABRICATION AND DURING SERVICE

by
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SUMMARY

The individual parts of the Alpha Jet carbon fibre plastic (CFRP) airbrake are subject to non-destructive testing by means of ultrasonics and X-rays during production. With these methods it is possible to detect flaws in laminates, such as delaminations, inclusions, cracks, porosity, pockets, incorrect grain, and density differences in the laminates. Also adhesive defects, like porosity, bad cohesive bonding, inclusions etc., in CFRP/CFRP, CFRP/alu, and CFRP/honey comb combinations can be detected. Quantity and size of the flaws detected are reported. Furthermore the experiences gained during the inspection of the prototype airbrakes by the time of the report are described. Prospects for the further proceeding in this field form the conclusion of the report.

INTRODUCTION

The first CFRP-part being produced in series at Dornier after a successful prototype flight test is the airbrake of the Alpha Jet (Fig. 1). Other CFRP-structures of the Alpha Jet such as the rudder and the elevator are still in the development stage. These structures are planned to be produced in series at a later date after a successful conclusion of their flight tests.

The most important components of this airbrake

- the airbrake shell
- and the spars

are made of CFRP-single laminates and bonded with each other (Fig. 2). Apart from the design development of the fibre construction it is also important to keep up with the reliable detection of flaws occuring during the production process. The testing of the laminates is necessary because the actual material and thus its properties only develop during the processing of the basic material (prepreg) in the production stage. This lecture will report on non-destructive tests that are carried out with the series airbrake at Dornier. The incoming inspection of the basic material is not included herein.

1. POSSIBLE FLAWS

The flaws that may be encountered in composite construction are:

external flaws on laminates
internal flaws in laminates
flaws in the adhesive joints

Apart from external flaws on laminates as for instance

- damage
- bad surface
- edge splitting
- surface cracks

etc.

that are visually detectable, non-destructive testing techniques have to be applied for the detection of the other flaws.

1.1 FLAWS IN LAMINATES

The most important flaws that may occur in a laminate (Fig. 3) are:

- wrong number of layers
- wrong positioning of layers
- irregularities due to curing errors
- voids
- porosity
- delaminations
- density variations
- inclusions
- cut fibres

For the first two flaws there is a possibility of indirect control. In the case of an insufficient number of layers the thickness of the laminate does not correspond to the desired value. Besides that, the laminate warps because of the asymmetric layer structure. This also happens if individual prepreg layers have not been placed properly. The detection technique for the remaining flaws will be discussed later.

1.2 FLAWS IN ADHESIVE JOINTS

This includes the flaws in the adhesive itself as well as the flaws that may occur for instance in the bonding mould.

Flaws in the Adhesive

The most important flaws are:

- lack of adhesive
- porosity in adhesives
- thick bonds
- unremoved protective film
- other inclusions in the adhesive

Other Flaws

- bad splice bonding
- wrong position of the components in the bonding mould
- defective cores
- separated cores
- water inclusions in the cores

2. DETECTABILITY OF THE FLAWS OCCURING DURING THE PRODUCTION PROCESS

Figure 3 and 4 shows that we could find the most of the major flaws in the laminates by means of ultrasonic testing and radiography. The same applies to bonding errors. Depending on the requirements the application of one of these techniques will be sufficient in some cases, in other cases both testing techniques will be applied.

2.1 ULTRASONICS

The most important techniques that have been successfully applied at Dornier are as follows:

- through-transmission-inspection
  - two transducers (transmitter and receiver) that are placed opposite each other
  - reflector plate method
- pulse-echo inspection

These techniques are generally known. Therefore, it is not necessary to discuss them in detail.

For the testing of series-produced parts it is advisable to use semi-automatic or fully automatic testing equipment for the gradual scanning of the test piece in order to obtain an exact localization of the flaws (C-scan). To this end the test piece is fully immersed in water (immersion technique) whereby the coupling between transducer and test piece is realized through the surrounding water. It is possible to apply the pulse-echo technique as well as the through-transmission inspection.

A more complete description of the "through-transmission" and "pulse-echo" test principle is shown in Fig. 5.

In both cases, if the receiver signal is less than the writing level the recording system records a "flaw". Through variation of the writing level it is possible to record major or minor flaws. Fig. 6 shows a C-scan of a laminate recorded by pulse echo principle in comparison with an X-ray picture of the same area. If the writing level is about 32 % of the monitor scale the C-scan corresponds absolutely with the X-ray. If it is lower (25 %) the smaller voids are not recorded. If it is higher (50 %) more minor flaws are recorded.

We found advantages in using of such test equipment with a recording system for the following reasons:

- quick testing
- high reproducibility
- recording of the test results
- optimal coupling

Further flaws that we detected by means of ultra-sonics are:

<u>in laminates</u>

- delaminations (Fig. 7)
- porosity (Fig. 7)
- inclusions

<u>in adhesives</u>

- lack of adhesive film (Fig. 8)
- no adhesive bonding (Fig. 8)
- inclusions in the adhesive film
- porosity in adhesives

2.2 RADIOGRAPHY

For the examination of CFRP-parts long-wave, faintly-penetrating X-rays are necessary. The proper radiation is provided by an X-ray tube with a beryllium window.

The detection of flaws in CFRP-laminates is rather difficult due to the fact that the expansion of flaws in the direction of the radiation is very small. However, if the equipment is properly adjusted, even the smallest flaws can be detected (Fig. 10). We could detect many hair-like voids. They run lengthwise of the grain and measure about

0.24 x 0.24 mm. The small porosities have an even smaller expansion of about 0.1 x 0.1 mm. Fig. 11 gives an idea of the efficiency of radiography. Thickness variations of 0.25 mm are easily detectable due to the different shades of grey. Resin rich areas and fibre rich areas causing change of density could also be located.

Even a paper shred that has been placed into a laminate of 3 mm appears faintly on the X-ray (Fig. 12). Its position is indicated by two arrows. In the adhesive joints we could also detect the following flaws:

- porosity in the adhesive film
- defective splice bonding
- core deformations (Fig. 13)
- water inclusions in the cores (Fig. 14)
- wrong position of the components

3. REFERENCE STANDARDS

Reference standards are necessary in order to provide adequate calibration of testing equipment used on production hardware. These standards should contain of the required sizes as specified by the acceptance criteria. The standards duplicate the configuration and cross sections of the production part with identical facing sheets, core, adhesive, etc. Fabricated within these standards are defects of known dimensions which allow us to establish optimum equipment calibration.

All standards are carefully sealed to prevent water or couplant leakage.

4. ACCEPTANCE CRITERIA

Because of the variation of stress levels for different components and different areas of the same component during flying, we subdivided the airbrake to several areas and defined different acceptance criteria for each area.

These criteria were defined in accordance with tests with parts and samples which have the same sizes of flaws as those which are acceptable.

5. INSPECTIONS DURING SERVICE

We have inspected four prototype-airbrakes by means of ultrasonic and X-ray after about two years of flying tests with the prototype airplanes. We couldn't find any change with respect to the initial state. In order to examine the behaviour of the CFRP-airbrake in long term operation we planned an extensive inspection programme.

The operating result of the airbrake shall be controlled and recorded for a limited number of aircraft of the flying units of the German airforce. According to the programme 2 to 4 airbrakes each will be dismantled after certain operating times (1, 2, 3, 4, 5 and 6 years) in order to examine whether there have been any changes in the overall structural behaviour and the material properties.

To this end a detailed logbook will be kept and a thorough inspection exceeding the normal inspection standard for all structural units will be carried out in order to detect any change with respect to the original state. Destructive tests with samples taken from airbrakes which have been in operation for up to 6 years are planned in order to obtain additional information concerning possible changes of the material properties. This programme is financed by the departmental section RÜ IV/1 and RÜFo V of the Federal Ministry of Defence.

6. PROSPECT

By means of these examples we have reported on the possibilities of radiography and ultrasonics. Although the field of application is still rather new it is already possible to detect a large number of major flaws with the above mentioned techniques and equipment. The adaption, further development, and new development of testing techniques and testing equipment for the CFRP-material will certainly increase the possibilities and further improve the reliability of the test results.

So far, for instance neutron radiography has only been applicable in the laboratories of the nuclear power plants. According to the latest information neutron radiography plants are already being developed as series production equipment for industrial use.

Another example is the fact that we are presently testing the improved application of radiography for the assessment of the bonded joints quality. This is done by means of the addition of an absorption substance to the adhesive whereby the detectability of defective adhesive joints is improved. These tests are carried out in cooperation with the RüFo V of the Federal Ministry of Defence.

Based on our investigations we believe that the problem of the economical, non-destructive testing of CFRP-parts can be solved in accordance with the requirements of quality assurance.

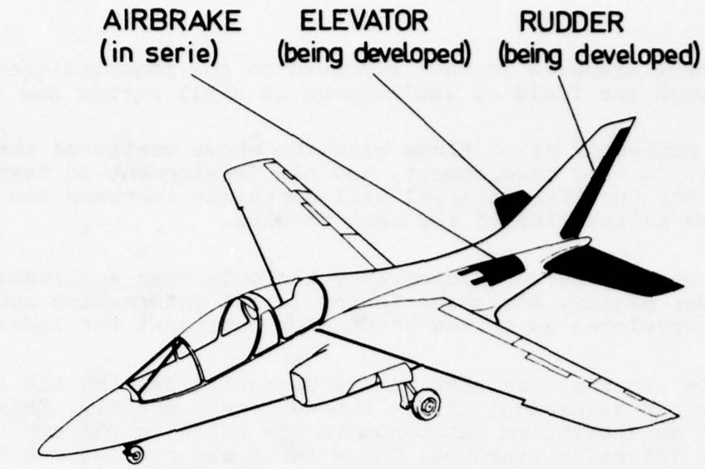


Fig.1 CFRP – structural components of α-jet

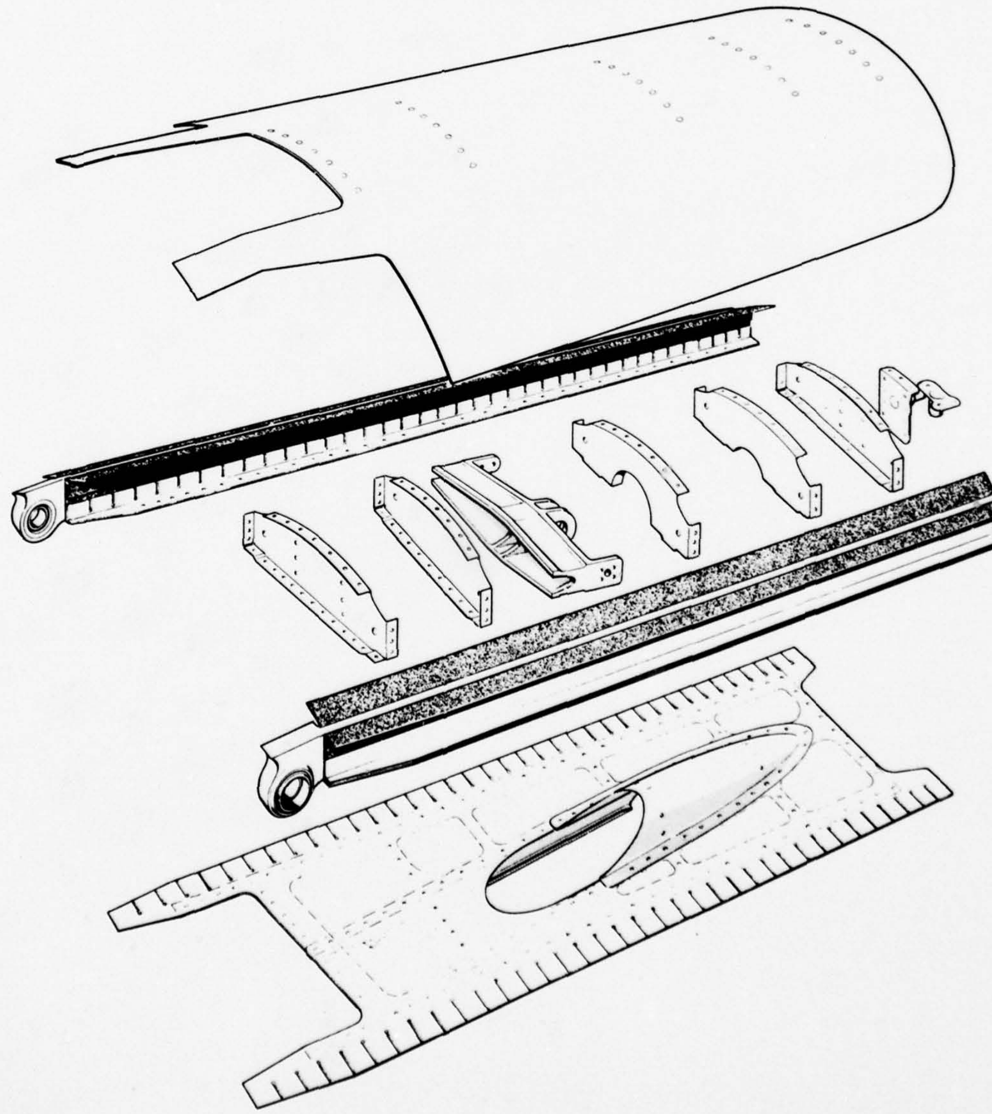


Fig.2 Airbrake of α-jet

	FLAWS	VISUAL	US-THR.-TRANSM.	US-PULSE-ECHO	RADIOGRAPHY
EXTERNAL	Bad surface	●			
EXTERNAL	Cracks	●			
EXTERNAL	Scratches	●			
EXTERNAL	Edge splittering	●			
INTERNAL	Wrong nr. of layers	●		●	
INTERNAL	Wrong positioning	●			
INTERNAL	Curing errors				
INTERNAL	Voids		●	●	●
INTERNAL	Porosity		●	●	●
INTERNAL	Delaminations		●	●	
INTERNAL	Density variations				●
INTERNAL	Inclusions		●	●	●
INTERNAL	Cut fibres				●

Fig.3 Detectability of flaws in laminates

	FLAWS	VISUAL	US-THR.-TRANSM.	US-PULSE-ECHO	RADIOGRAPHY
ADHESIVE	Lack of adhesive	o	●	●	●
ADHESIVE	Bad adh. bonding		●	●	
ADHESIVE	Porosity		●	●	●
ADHESIVE	Thick bond		●		●
ADHESIVE	Not removed protective film		●	●	●
ADHESIVE	Other inclusions		●		●
OTHERS	Bad splice bond				●
OTHERS	Wrong position				●
OTHERS	Defective core		●	●	●
OTHERS	Separated core				●
OTHERS	Inclusion of water				●

o no fillets

Fig.4 Detectability of flaws in adhesive joints

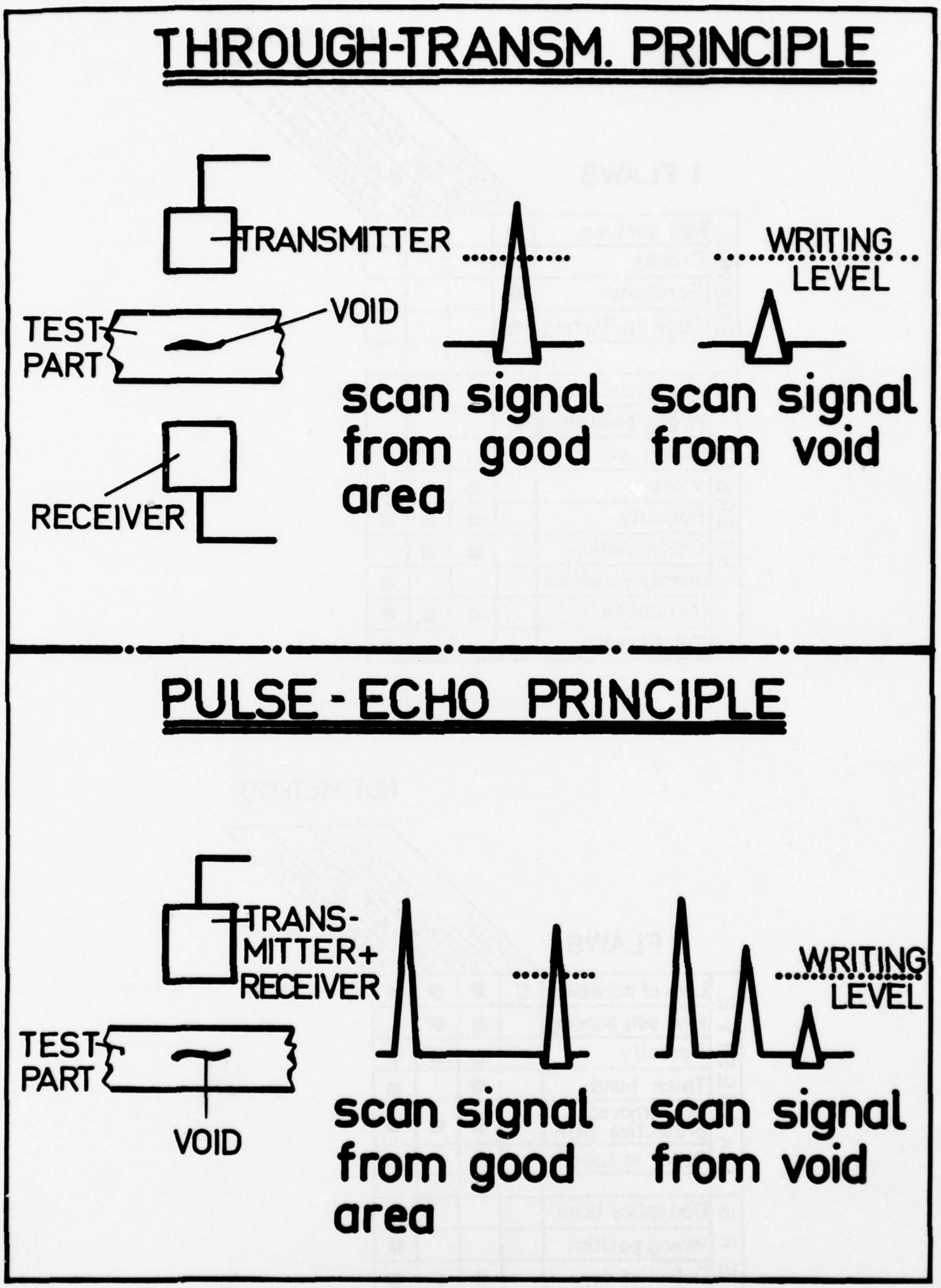


Fig.5 Ultrasonic scanning principles

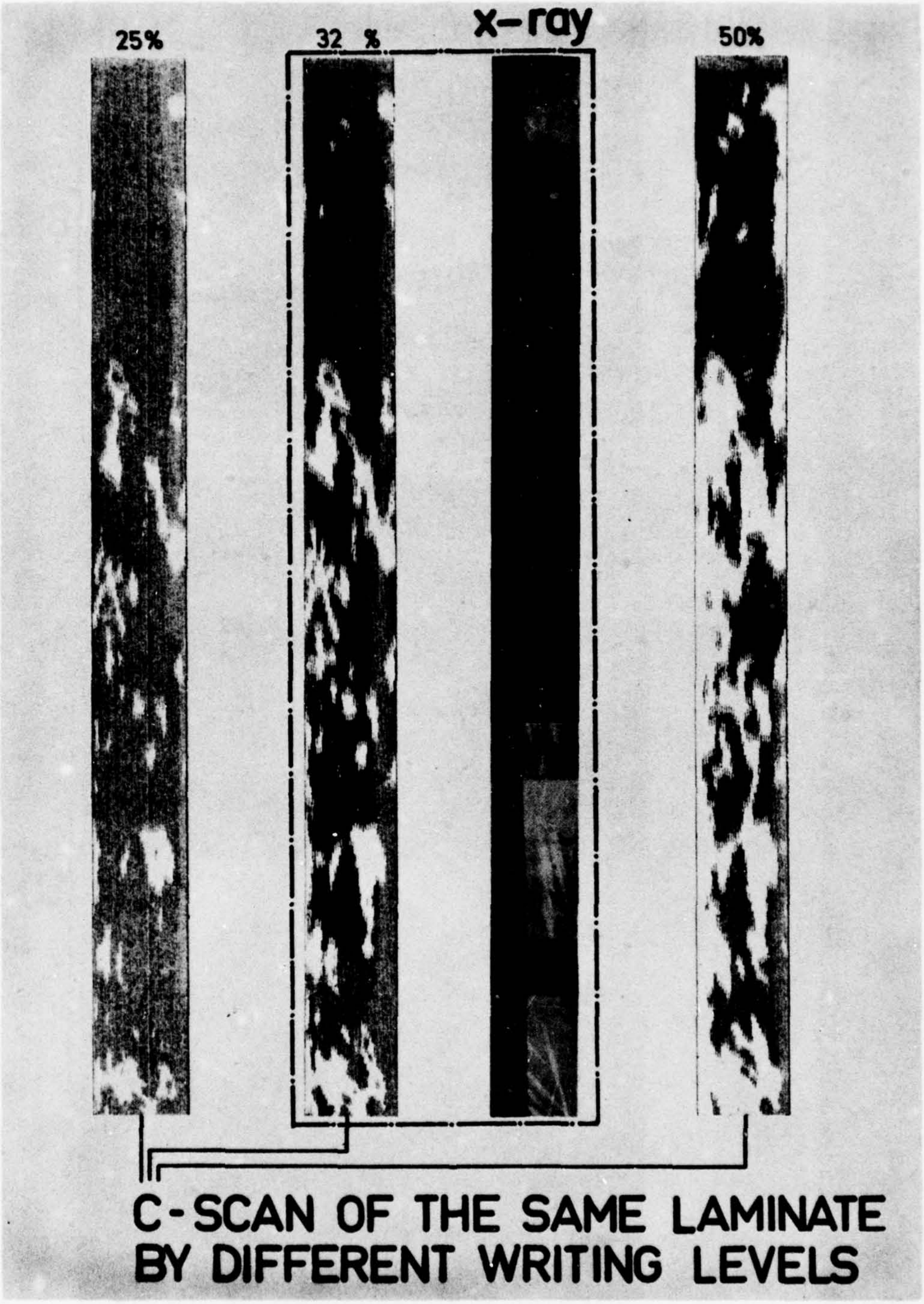


Fig.6 C-scan of a defective laminate in comparison with an X-ray

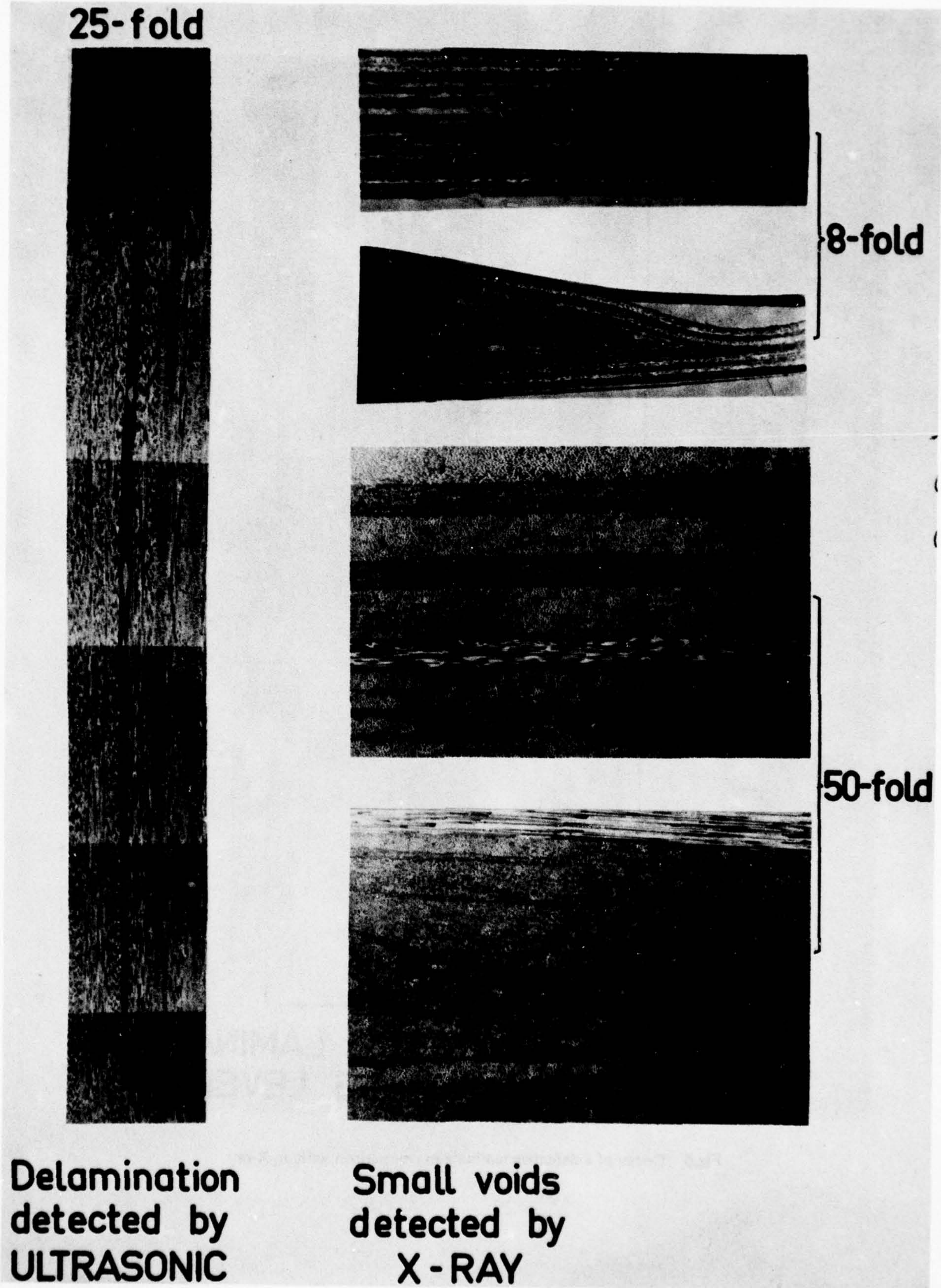
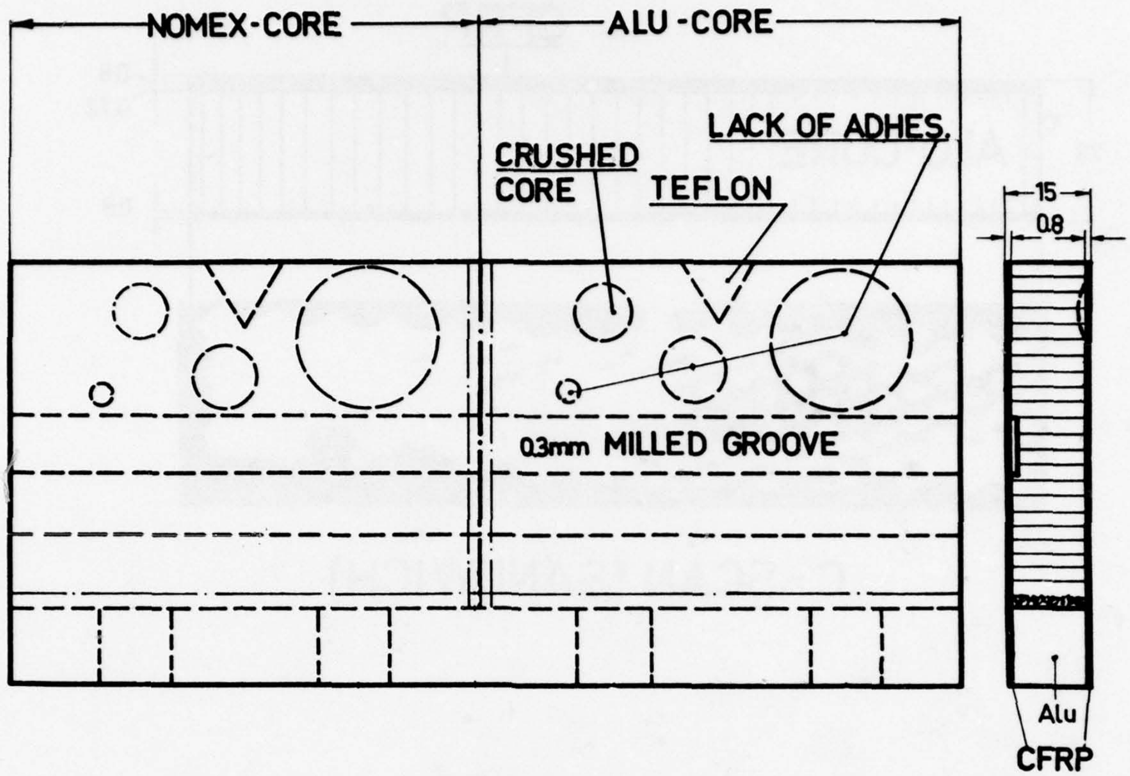


Fig.7 Micrographs of a delamination and voids



C - SCAN

Fig.8 C-scan of a standard

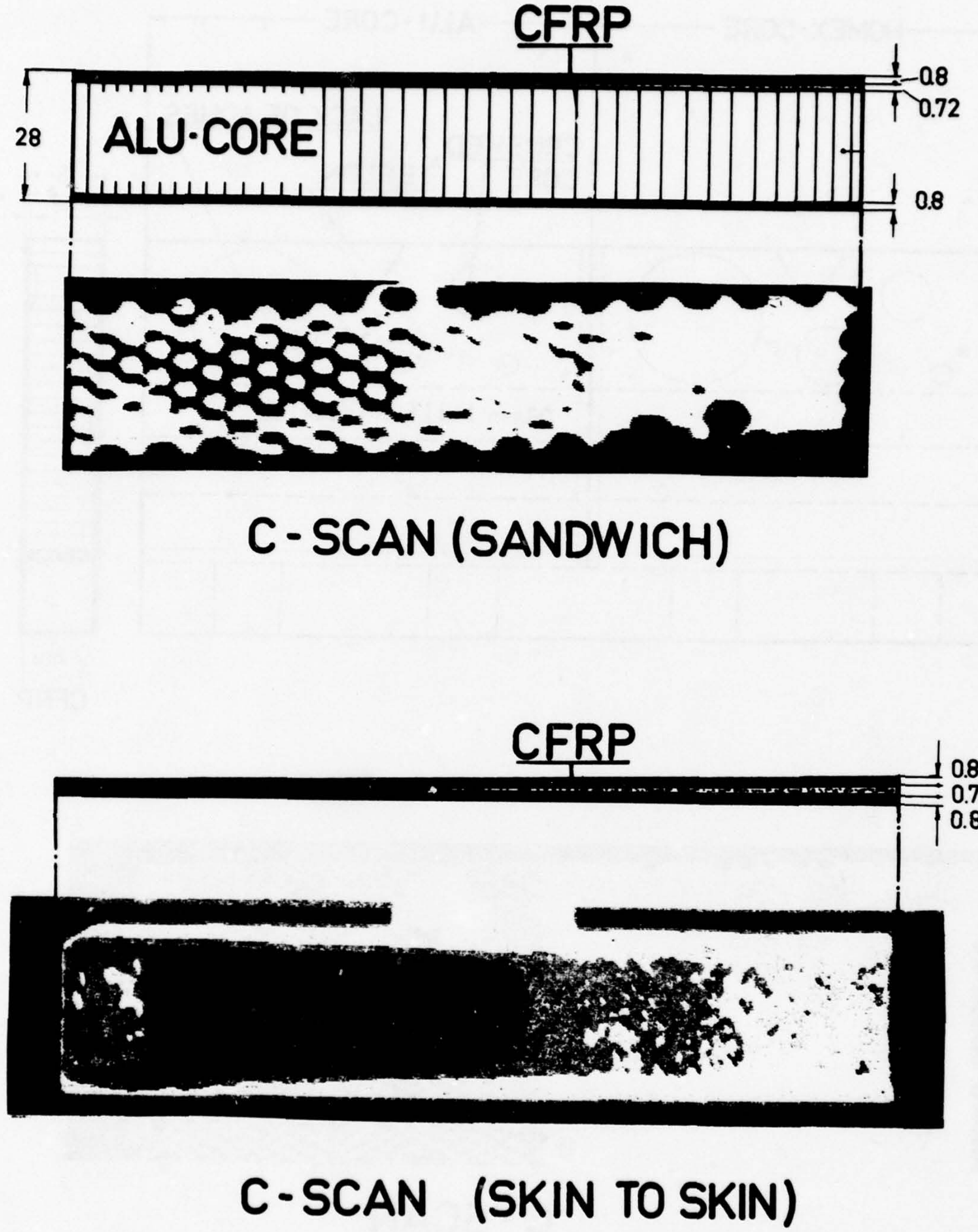


Fig.9 C-scan on increasing thickness (porosity) of the adhesive

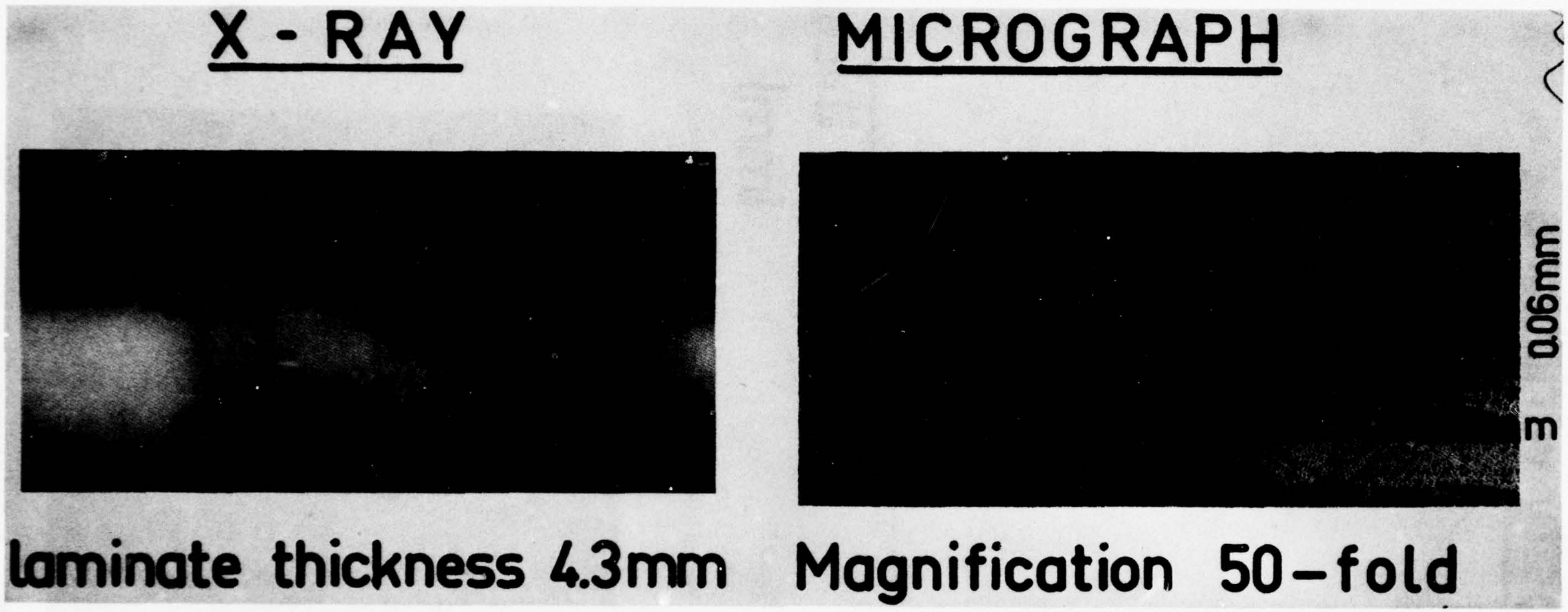


Fig.10 X-ray of a laminate with hair-like voids

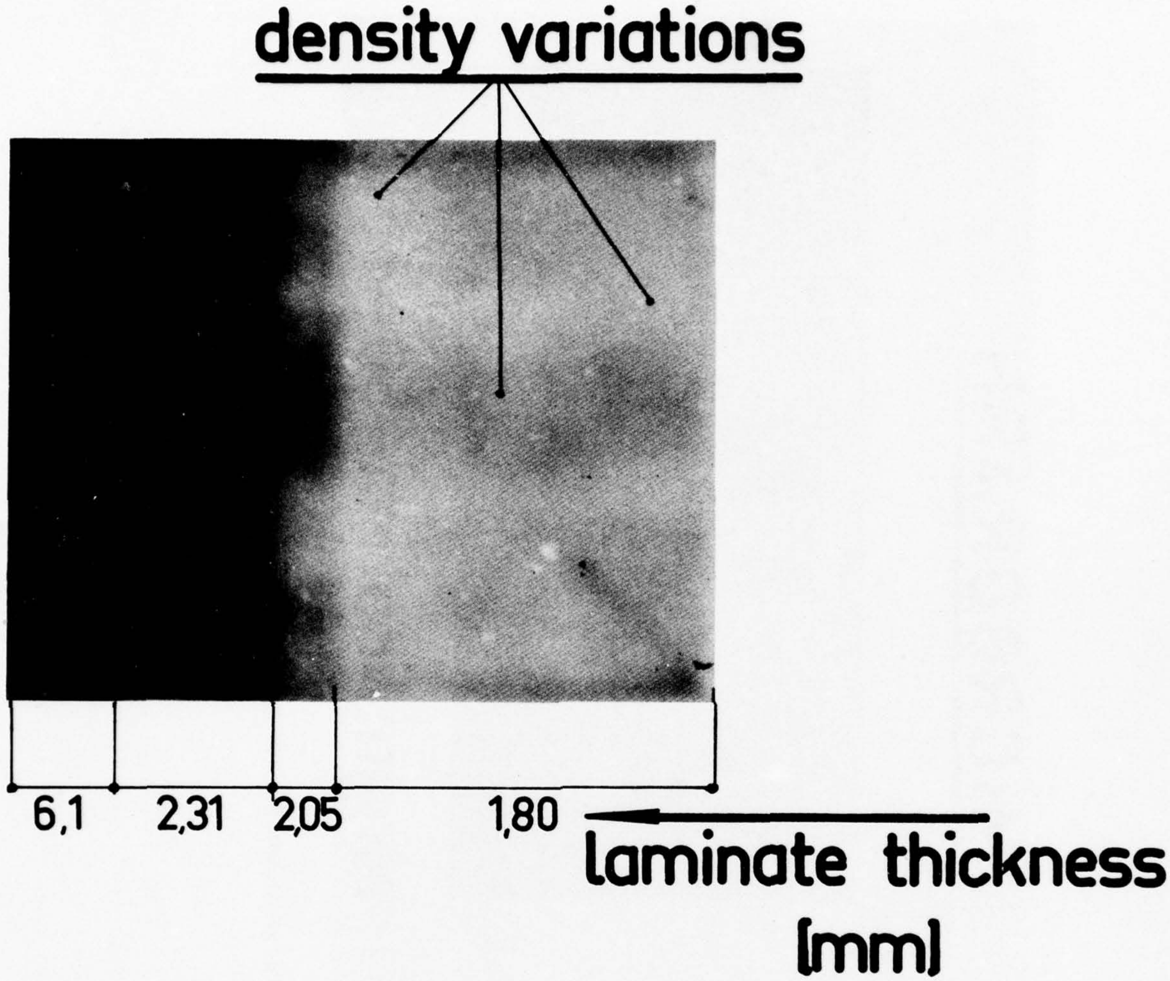


Fig.11 X-ray of a laminate with different thicknesses and densities

Fig.12 X-ray of a laminate with an inserted paper shred

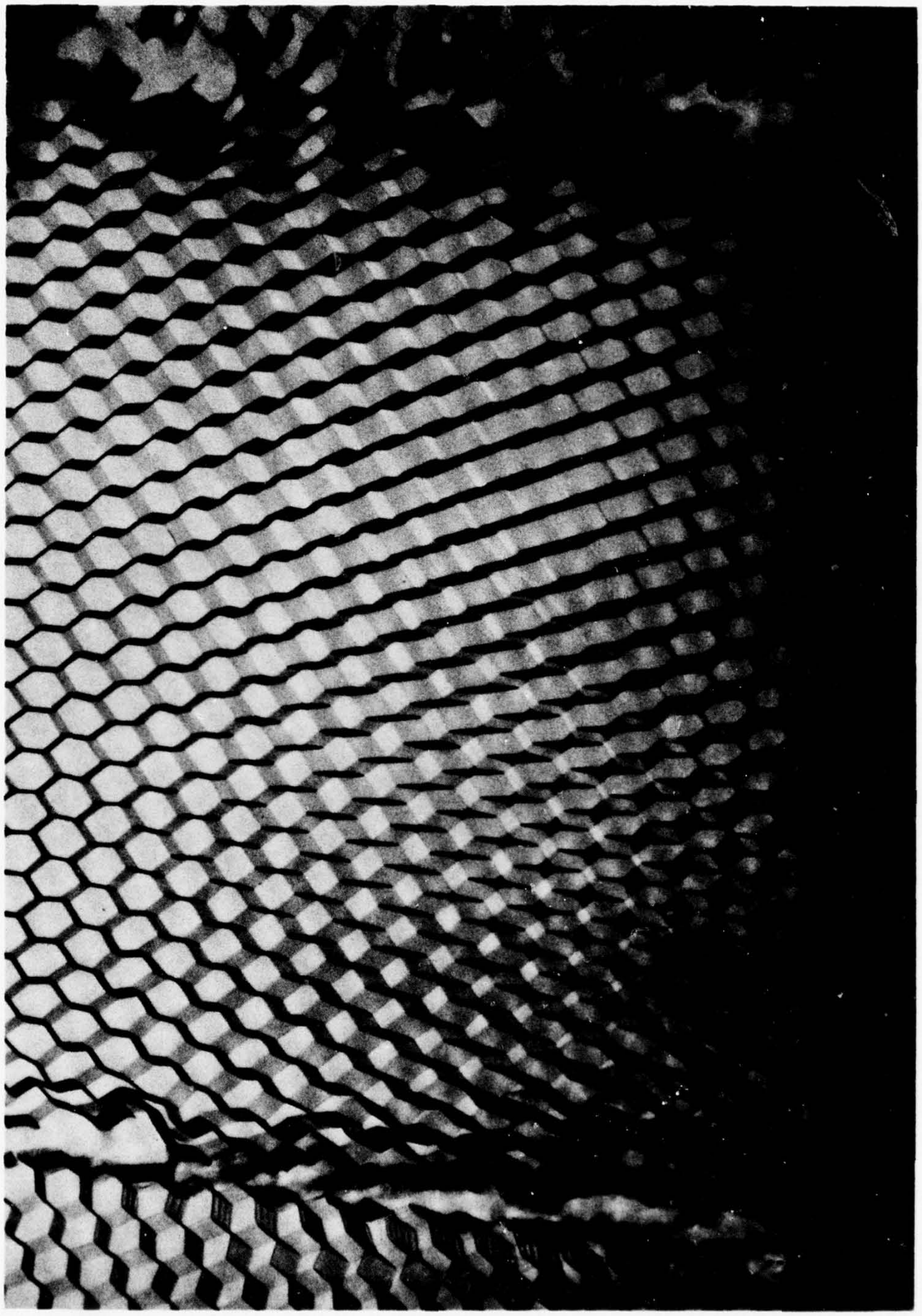


Fig.13 Bad splice bonding and deformed core

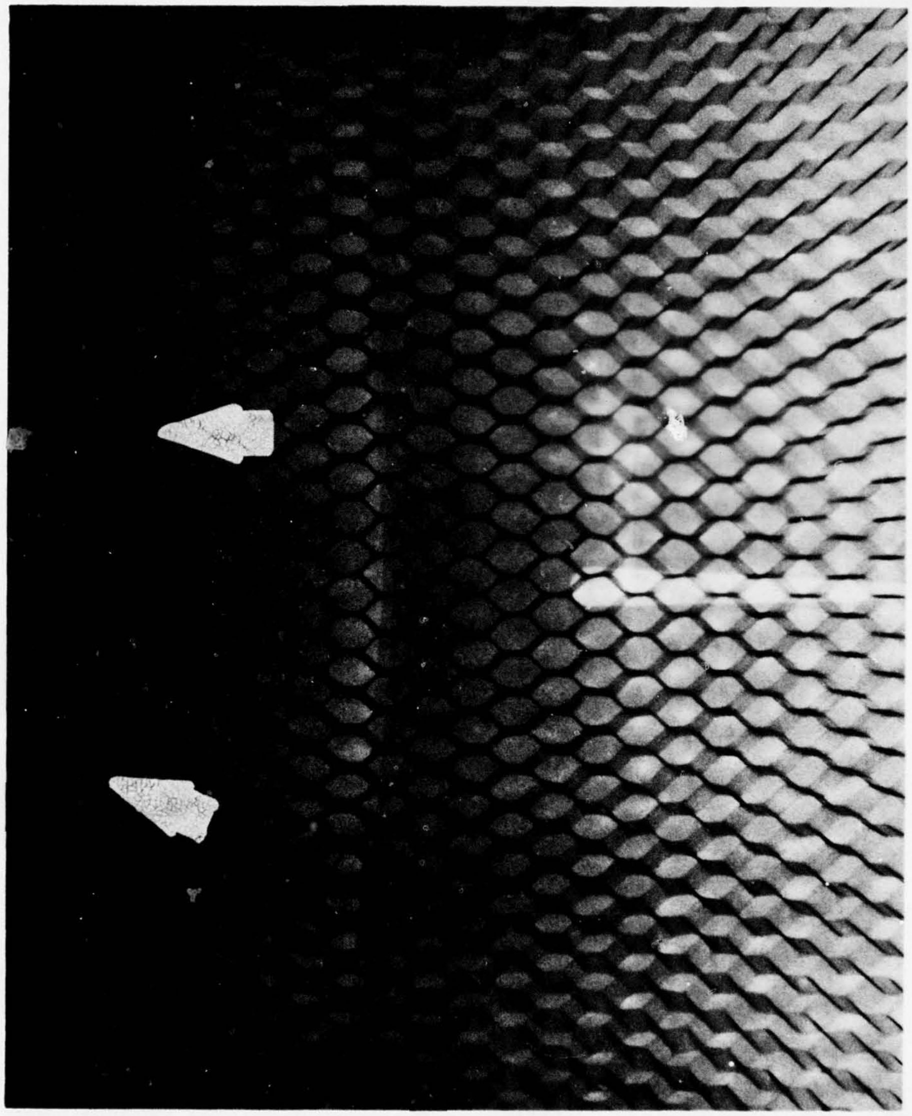


Fig.14 Water inclusions in core

DETECTABILITY OF FLAWS IN BORON AND CARBON COMPOSITE PARTS

by

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SUMMARY

In the current technology programs BFRP and CFRP composite structures are in development. The experiences on non-destructive testing gained out of this work are presented.

The non-destructive testing is carried out on semifinished parts as well as on composite structures during the different stages of fabrication process. The following test methods and devices have been investigated and applied: soft X-ray technique, ultrasonic, acoustic flaw detector, sonic resonator, holography, and tapping test.

It will be shown what kinds of faults in which dimensions are found in a composite part with the above mentioned test methods. Finally the capacity of the mentioned test methods for practical use will be critically discussed.

1. INTRODUCTION

VFW-Fokker's technology programs embrace the manufacture of various fibrous composite parts. Shown in fig. 1 is one of them, the front landing-gear door with Nomex-honeycomb core and Kevlar/carbon fiber top skin for the short-haul airliner VFW 614.

The structure of a flight spoiler for the VFW 614 comprising a boron fiber skin and Nomex--honeycomb core is substantially more complex. Fig. 2 shows a routine check of the spoiler with the acoustic flaw detector.

Another fibrous composite part is the subsonic intake ramp shown in fig. 3.
This ramp consists of a sandwich structure with aluminum honeycomb core, 2 mm thick CFRP laminates as top skins, and aluminum fittings bonded between the laminates for the partial, punctiform force introduction. The build-up of the subsonic intake ramp is shown in fig. 4.

In order to ensure the quality of these composite parts various non-destructive test procedures have been investigated and applied. The experience gained will be presented in this paper. In detail only the non-destructive test procedures performed on the intake ramp will be explained, because they are to some extent representative for all the other parts.

2. TEST PHILOSOPHY

The selection of the non-destructive test procedures to be used was based on the test philosophy that only flaws occurring during the manufacture of the individual parts or during the assembly need to be detected by means of these procedures. A reduction in the quality of the part resulting from poor prepregs will be safely eliminated by other test procedures, carried out before.

Various steps are necessary to manufacture the intake ramp. Thus, the semi-finished products of each individual operation can be checked applying non-destructive test procedures.
The individual operations are:
- manufacture of the CFRP laminates (approx. 2 mm thick);
- bonding of the laminates to the aluminum honeycomb and fittings including GFRP Z-sections in one shot;
- bonding of the honeycomb wedge with GFRP top skin to the CFRP top skin.

Quality control of the individual operations can be subdivided into two phases, the first phase being to control the compliance with the optimized manufacturing parameters during production. But even the most careful control cannot prevent the slipping in of flaws during individual operations. These flaws must be detected without fail by means of adequate NDT methods during the second control phase.

During the manufacture of laminates the following flaw sources are possible:
- various reasons are possible for the occurrence of single voids or even porosity covering a major area of the laminate;
- broken and cut filaments may occur during manufacture of the laminates;
- varying resin flow may result in a desorientation of the fibers within the laminate, but also in resin-rich and/or resin-starved areas;
- various reasons are possible for foreign object enclosures in the laminate, e.g. residues of unremoved protective films;
- improper processing of the finished laminate may result in delaminations and cracks.

Further flaws may occur during assembly of the intake ramp:
- splice defects between honeycomb/honeycomb and honeycomb/aluminum fitting;
- insufficient bonding between CFRP laminate and honeycomb;
- unbonds between CFRP laminate and aluminum fitting;
- unbonds between CFRP and GFRP;
- delaminations and cracks in the bonded CFRP laminate due to subsequent processing operations;
- crushed cores.

In principle several NDT test methods can be used for detection of the flaws mentioned. We have proved the following:
- soft X-ray technique
- acoustic flaw detector from Inspection Instruments Ltd.
- ultrasonic with immersion through-transmission and with immersion pulse-echo
- tapping test
- sonic resonator from North American Aviation
- holography with real-time (thermal stressing) and with time-average (vibrate stressing).

The indication values obtained by these test procedures and equipment have been proved by us using test specimens similar to the parts with incorporated, well defined flaws.

3. TEST SPECIMENS WITH DEFINED FLAWS

For the purpose of these investigations we produced several of the test specimen types shown in fig. 5 with differing defined flaws. Various methods were used with these test specimens to simulate as realistic as possible flaws of the type described earlier.

Apart from these test specimens we also made a so-called step wedge as well as penetrameters of CFRP laminates with differing thicknesses which are shown in fig. 6. These small CFRP laminates were provided with 4 holes having once, twice, three or four times the diameter of the respective laminate thickness. The penetrameters used for the investigations were 0.1, 0.2, 0.4, 0.6, 0.8 and 1.0 mm thick.

With the test specimens we were able to prove the detection sensitivity of the various test procedures. The experience gained with be detailed below.

4. X-RADIOGRAPHY (SOFT RAYS)

Due to its physical principle, X-radiography indicates density differences in the specimen. Therefore, it can be used to indicate voids, inclusions, broken or cut filaments, resin-rich or resin-starved areas as well as fiber orientation in the laminates if the resulting density differences produce a radiation attenuation sufficient to cause a contrast on the film. As the density of CFRP laminates is substantially lower than that of metals normally to be tested, the density differences which may be produced by flaws and which will have to be resolved are much less distinct.

Therefore, the flaws in laminates cannot be resolved with normal radiation energies. In order to determine radiation energies sufficient to obtain an adequate contrast on the film, an exposure chart was established for the CFRP wedge. The resulting values show that - dependent upon the laminate thickness - the required radiation energy must be between 10 to 30 KV.

Radiographs of various CFRP laminate thicknesses with superimposed penetrameters were produced in order to determine the void sizes that can be detected at different laminate thicknesses with soft X-rays. For these radiographs the penetrameters were, as practised with metals, superimposed on the side turning away from the film. The radiographs thus produced were used to determine the safely and the only just perceptible hole diameter of the various penetrameters. The results are shown in fig. 7. The behavior of the curve indicates that the detectability of the relative void size increases with the laminate thickness. Altogether, the resolvable void size is inferior by a factor of 2 - 3 compared with that which is normal to metals. This must be attributed to the inhomogenous laminate structure. So this test technique permits the safe detection of single 0.4 diameter voids at a laminate thickness of 2 mm or 0.8 mm diameter voids at 8 mm thickness.

Another test with X-radiography was meant to determine areal inclusions, such as residues of unremoved protective films, that may be detected in a laminate.

Fig. 8 is a radiograph of a 2 mm thick CFRP laminate of a density $\gamma = 1.57$ g/cm^3 including a 25 μm thick Teflon film of a density $\gamma = 2.1$ g/cm^3. The percentual difference of the areal density in this radiograph is 0.51 %.

Fig. 9 shows the percentage differentiable areal density that can be detected as a function of the laminate thickness. The results show that inclusions having a diameter of more than 5 mm and causing a differentiable areal density of 0.5 % can be safely detected. The limit detectability is 0.2 %. So this radiographic technique permitted, for example, the detection of Teflon spray simulating a poor bonding quality in the middle of 2 mm thick laminates (flaw diameter approx. 30 mm).

X-radiography with soft X-rays is also suitable for the investigation of fiber orientation which is most important for the strength and stiffness behavior of the laminate. With thin laminates (approx. 2 mm), the direction of the fibers is often directly visible on the radiograph; but this is not true for thicker laminates. However, a control of the manufacturing process is possible

by incorporating - parallel to the tape direction - single thin glass fibers with a density $\gamma = 2.5\ g/cm^3$ or single carbon fibers vapor-deposited with a heavy metal (such as cadmium) when producing the laminate. These fibers make it possible to see the shifting of the carbon fibers on the radiograph. Fig. 10 shows a radiograph of a 2 mm thick, unidirectional CFRP laminate with cadmium--vapor-deposited carbon fibers incorporated parallel to the direction of the fibers. This laminate was so fabricated that the carbon fibers changed their direction. That was to check whether the individual, cadmium-vapor-deposited carbon fiber would behave in the same manner as other fibers. The radiograph proved just that. Therefore, this method offers a good opportunity to subsequently determine very accurately the fiber orientation at locations critical with regard to manufacture. Here we have proved carbon fibers. When we have to prove boron fibers, there is no problem, because the tungsten core in the filaments has a high density.

Flaws such as crushed cores and splice defects between honeycomb/honeycomb as well as honeycomb/aluminum fitting cannot only be easily determined in laminates but also on the finished part. But these methods generally do not require low radiation energies.

5. ULTRASONIC INSPECTION

Non-destructive ultrasonic material inspection comprises the introduction of an ultrasonic beam into a material and the measurement of its change after having passed the material. Thus ultrasonic inspection can be used, as a general principle, for the detection of any material flaws changing the propagation of ultrasonics in a way other than that of the basic material. Propagation within a material will be influenced by several factors such as absorption, dispersion, diffraction, refraction, and reflexion. Therefore, the procedure is suitable for the detection of voids, inclusions, poor bondings, delaminations, resin-rich and resin-starved areas as well as crushed cores. Splice defects can also be determined by this procedure. For the present testing process, the indicative values of the through-transmission and the pulse-echo techniques were checked.

In the through-transmission technique, a continuous sound wave or sound pulse is emitted by a transmitter and - after having passed the workpiece - picked up and evaluated by a separate receiver. Incoming sound intensity or sound pressure is used for the evaluation. The delay time of the sound pulse is of secondary importance for this evaluation. A uniform probe-to-specimen contact, however, is very important for this test procedure as contact fluctuations of both probes result in considerable indications on the CRT and thus produce apparent flaws. In order to avoid problems of this kind, the investigations were carried out in a water bath assuring an ideal, uniform probe--to-specimen contact. This system was used not only for the testing of CFRP laminates themselves but also of the sandwich structure comprising CFRP top skins and an aluminum core. The principle of the test device and the results obtained for laminates are shown in fig. 11. The tests were performed with a 5 MHz probe having a diameter of 10 mm. The results can undoubtedly be improved if a focused transmitter is used.

The same test setup was used for testing the assemblies. For the aluminum honeycomb structure test frequencies of 2 MHz as well as 5 MHz were used. In both cases, sound energy sufficient for evaluation was picked up by the receiver. On the other hand, tests with a spoiler comprising a boron top skin and a Nomex honeycomb core showed that at 5 MHz, only insufficient energy reaches the receiver. The results for 2 MHz of the through-transmission technique with sandwich test specimens are illustrated in fig. 12. It was noted that the sound amplitude in the receiver varies only slightly for flawless areas. However, unbonded areas between laminate and honeycomb result in a considerable amplitude drop. The reason for this is that the ultrasonic beam is reflected at these points resulting in a considerable attenuation. But splice defects are also detected as the absorption at these points is smaller than with a good spliced connection due to lack of splice material. The smallest test effect was noticed with crushed cores; however, it still exceeds the noise level although the incorporated honeycomb flaws were relatively small.

The test results obtained with the pulse-echo technique for sandwich test specimens were useless. On the other hand, the test results for laminates, and particularly CFRP aluminum bondings were positive. But it is impossible to go into details in this paper.

Care has to be taken in the case of both, the through-transmission and the pulse-echo techniques, that no water enters the defective areas, particularly unbonded areas and delaminations, for this would result in a much less apparent flaw.

6. ACOUSTIC FLAW DETECTOR

The acoustic flaw detector (fig. 13) is a device used to measure the mechanical impedance of thin-walled laminates and bonded metal sheets. The probe of the device is provided with two piezoelectric crystals, one of them acting as transmitter and the other one as receiver. In order to excite the probe so that it generates oscillations, a sinusoidal alternating voltage - its frequency being infinitely variable between 1 and 8 kHz - is applied to the transmitter crystal. This transmitter partially excites that part so that the latter generates oscillations which are directly, i.e. without the aid of a probe-to-specimen contact medium, transformed into an electrical signal by the receiver crystal. This input signal passes various amplifier stages and may be evaluated not only with regard to its amplitude of oscillation but also according to the phase position.

Due to its physical principle, this device can be used to detect delaminations in CFRP laminates or unbonded areas of the laminate/honeycomb and laminate/aluminum fitting. The operating mode of the flaw detector requires a representative test specimen with adequate, defined flaws for each bonding combination and each laminate thickness. The test specimens are used to check whether the

device responds to flaws; furthermore, they are applied to achieve for each flaw type optimum adjustment data on the device.

The test specimens mentioned earlier were checked by means of the acoustic flaw detector, the results indicating that delaminations with a diameter of more than 15 mm can be detected without any doubt in a CFRP laminate. However, poor bondings simulated by incorporating Teflon spray could not be detected quite definitely. Artificially generated delaminations in laminate boundary regions, on the other hand, were easy to detect. The device is also well suitable for the detection of unbonded areas between laminate and honeycomb; the same applies to unbonded areas between laminate and aluminum fitting. In both cases the incorporated flaws of 20 mm dia. could be detected beyond any doubt. Crushed cores were also partially detected by the acoustic flaw detector. The major advantage of the device being the fact that no contact medium is required for the probe. Measurements showed that laminates with a thickness exceeding 2.5 mm assume a stiffness obviously strong enough to prevent deeper flaws from being safely detected.

It must be mentioned, however, that the operation of the device requires a certain skill, for there may occur oscillations in thin-walled parts which result in indications but are no real flaws.

7. TAPPING TEST

The tapping test can also be used to detect delaminations and poor bondings. In general, however, testing with the acoustic flaw detector is more sensitive and less dependent on staff.

8. SONIC RESONATOR (NAR)

The principle of this test device is based on the fact that oscillations of the crystal in the probe depend upon the elastic behavior of the structure to be tested. These varying oscillations of the crystal are indicated on a measuring instrument and are used for the evaluation of flaws. Therefore, any kind of flaws resulting in a partial change of the elastic behavior of a part can be detected by means of this instrument. Normal test frequencies of the sonic resonator (fig. 14) are in the threshold range between audible and ultra sound.

The abilities of the sonic resonator with various probes were investigated by means of the existing test specimens with defined flaws. Results showed that poor bondings and delaminations can be detected. A sufficiently large flaw indication exceeding the noise level will be obtained only if the flaw is larger than or at least as large as the probe diameter. As the probes have a relatively large diameter, only unbonded areas and delaminations with a diameter of more than 25 mm can be safely detected by this device.

9. HOLOGRAPHY

Non-destructive testing of parts by means of holography is essentially based on the assumption that faulty parts show a different surface deformation under load than faultless parts. If this requirement is met with regard to the test procedure, the interference pattern of the part under load shows irregularities which imply a flaw. Several photographic techniques can be used to establish a holographic interferogram. The success of this test procedure depends to a great extent also on the kind of load applied to the part.

The known test specimens with defined flaws were subjected to two different kinds of holographic tests (fig. 15). For the first test the so-called real-time technique with thermal loading was used. The part was heated either on its front or on its rear side by approx. 1-2°C by means of an areal radiator. During the heating phase the continuously produced interferograms were stored on a magnetic tape via a TV camera. This technique enabled us to determine most of the defined flaws as such. However, there were other irregularities in the interference pattern of the interferograms which might also be interpreted as flaws. Furthermore, it was noted that even parts which had to be called flawless showed irregularities in their interferogram that could not be explained by the structure of the parts. On the whole, it must be said that it is very difficult to interpret interferograms clearly as the flaw indications of this holographic technique do not differ very much from indications of technically acceptable areas.

Therefore, another holographic method was investigated. The test specimens were excited with a piezoshaker (up to 150 KHz). The interferogram was photographed by means of the so-called time--average technique. The vibrations applied result in loops and nodes on the surface of the part thus generating a very particular interference fringe pattern on the photographic plate. With this method, flaws in the part are detected on the basis of irregularities of the interferogram due to a changed vibration behavior of the surface as shown in fig. 16. It can be seen that the faulty area is clearly indicated. This method will be further investigated with regard to the present test case.

10. CONCLUSION

Our investigations showed (fig. 17) that no test procedure is able to detect reliable every flaw foreseen by the test philosophy. Only a combination of in this case two test procedures can be expected to determine any flaws with sufficient accuracy.

X-radiography with soft X-rays is an excellent means of detecting voids, inclusions, fiber direction, resin-rich or resin-starved areas, splice defects, and crushed cores. On the other hand, delaminations or unbonded areas are detected only if produced by an inclusion.

Ultrasonic inspection within the through-transmission technique is well suitable for the detection of delaminations and poor bondings; the other flaws described will be detected but their indication is considerably inferior.

If these two test methods are combined in a sensible way for the non-destructive testing of individual workpieces or the entire part, then the safe detection of all relevant flaws having a technically sufficient size poses no problem at all. Thus, the quality of a part is adequately assured after its completion by means of non-destructive test methods.

The continual on-line maintenance inspection of a part is quite a different thing; the application of the two methods suitable for production control is very limited as far as a continuous non-destructive inspection during maintenance is concerned.

At present, the other test methods investigated have to be used in such cases although their indicative value is far from being adequate, as our investigations have shown. Therefore, it is our opinion that we need improved non-destructive test facilities for the current maintenance work.

Figure 1. VFW 614 FRONT LANDING-GEAR DOOR with NOMEX HONEYCOMB CORE and KEVLAR/CARBON FIBER TOP SKIN

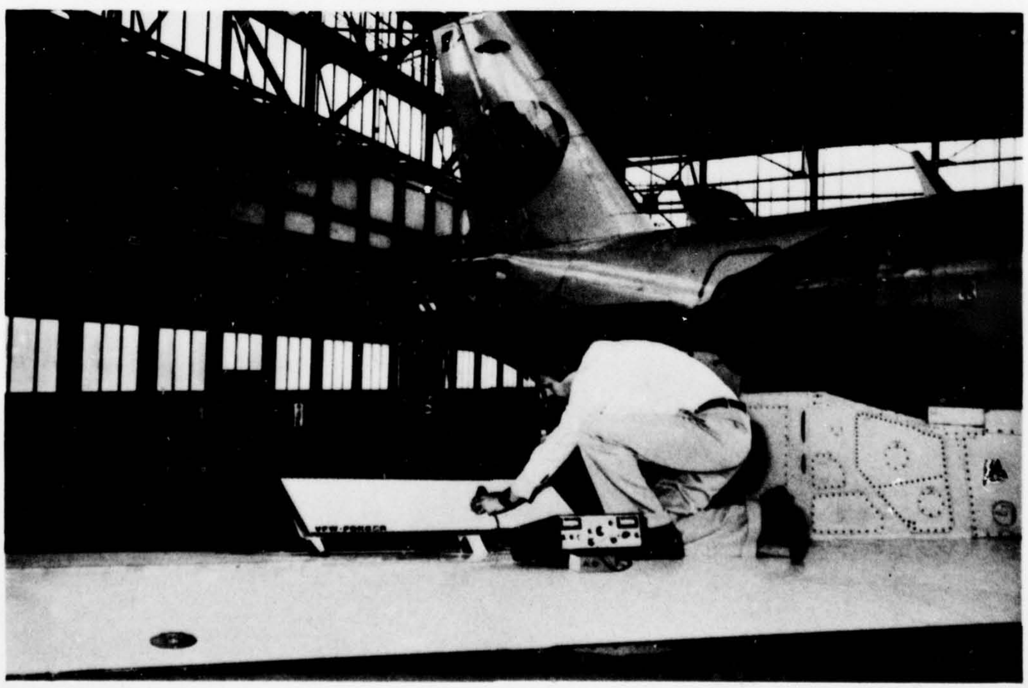


Figure 2. VFW 614 FLIGHT SPOILER with NOMEX HONEYCOMB CORE and BORON FIBER SKIN

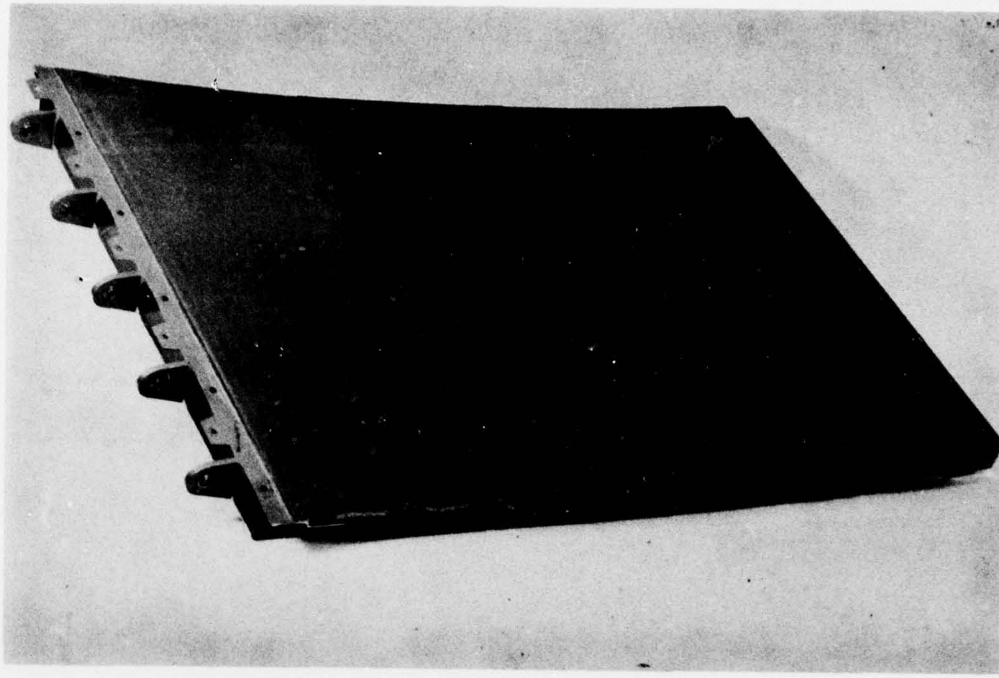


Figure 3. SUBSONIC INTAKE RAMP of FIBROUS COMPOSITE PARTS

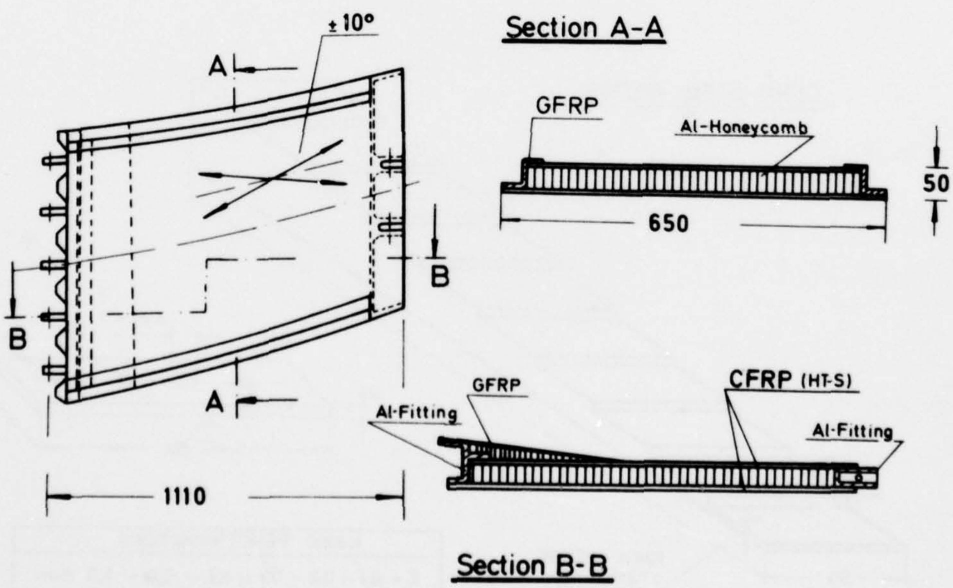


Figure 4. BUILD-UP of the SUBSONIC INTAKE RAMP of FIBROUS COMPOSITE PARTS

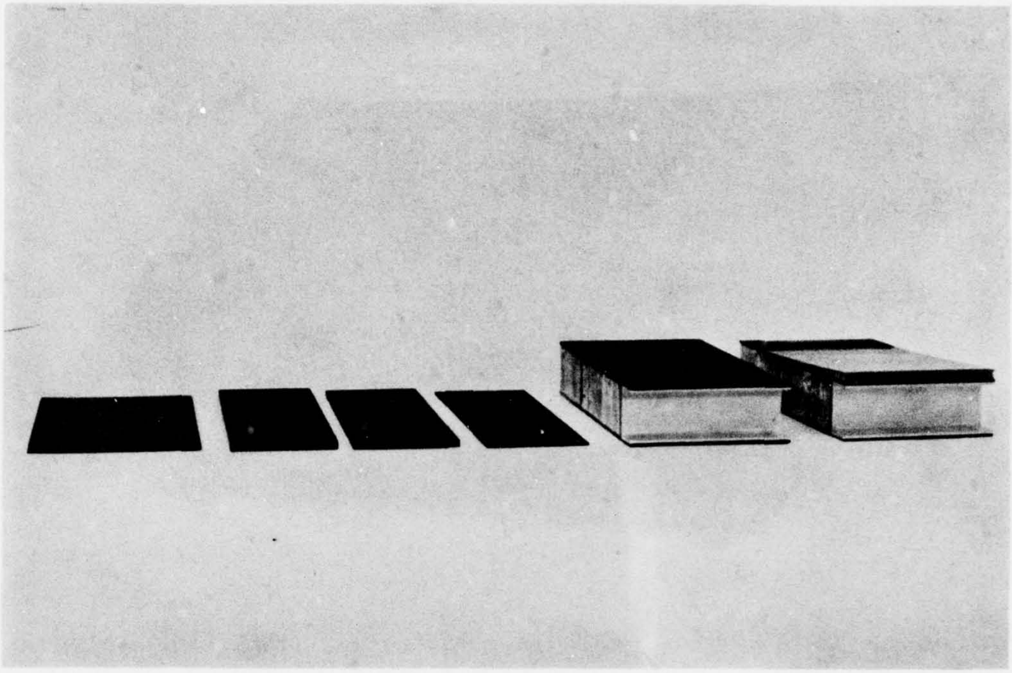


Figure 5. VARIOUS TEST SPECIMENS with DEFINED FLAWS

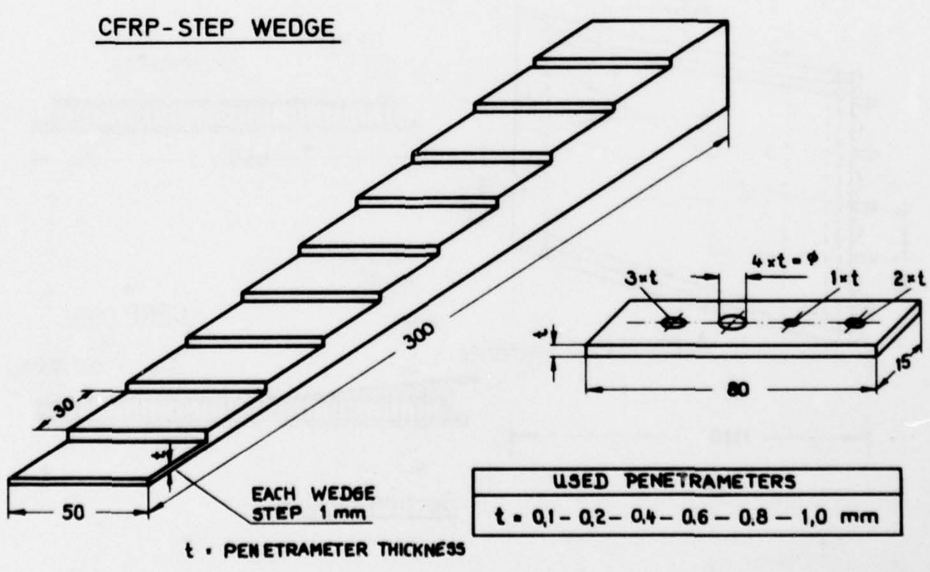


Figure 6. CFRP STEP WEDGE and PENETRAMETERS used for SOFT X-RAY TECHNIQUE

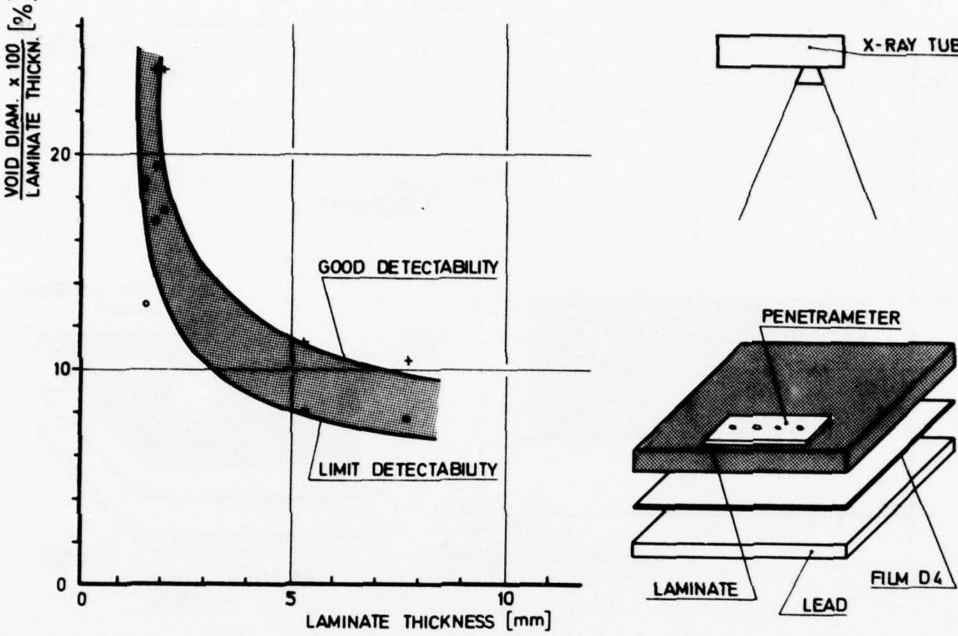


Figure 7. DETECTABILITY of VOIDS in CFRP LAMINATES by SOFT X-RAY TECHNIQUE

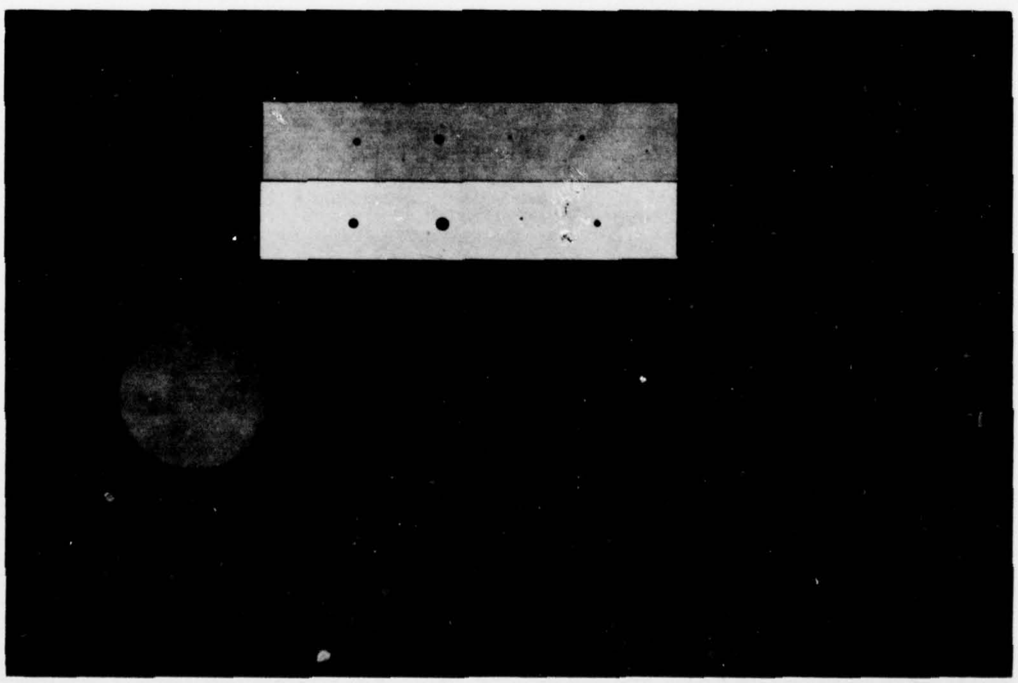


Figure 8. RADIOGRAPH (10 KV) of a 2 mm thick CFRP LAMINATE with INCLUSION (0,51 % DIFFERENCE AREAL DENSITY) and PENETRAMETERS 0,2; 0,4; 0,6 mm thick

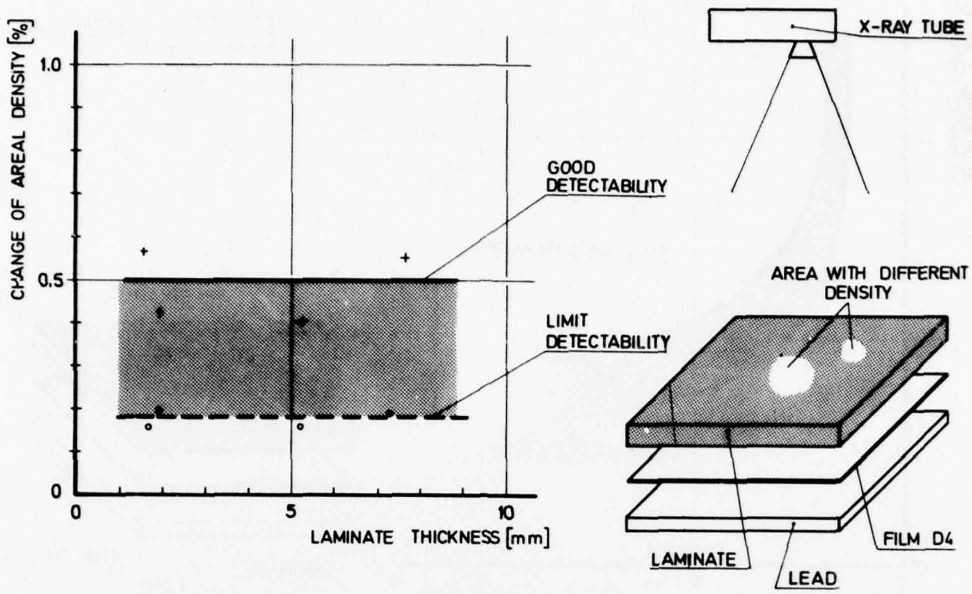


Figure 9. DETECTABILITY of DIFFERENT AREAL DENSITIES in CFRP LAMINATES by SOFT X-RAY TECHNIQUE

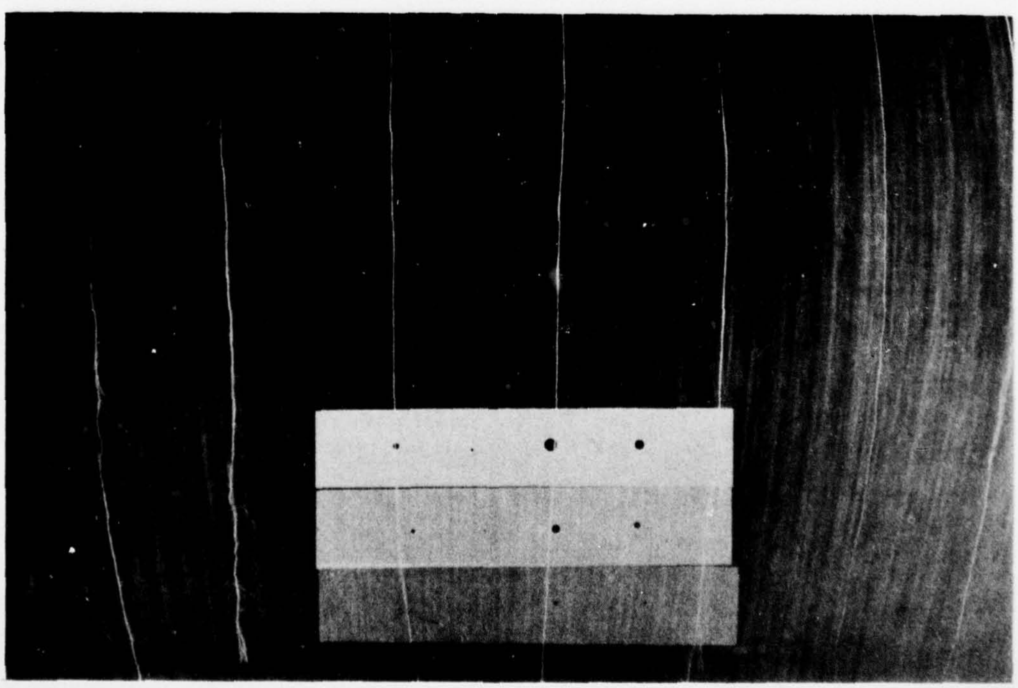
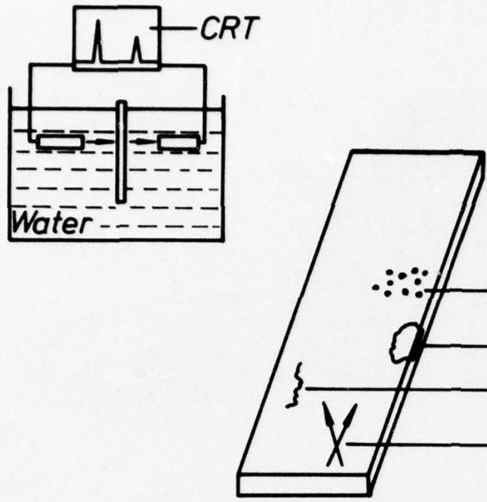


Figure 10. RADIOGRAPH (10 KV) of a 2 mm thick UNIDIRECTIONAL CFRP LAMINATE with CADMIUM-VAPOR-DEPOSITED CARBON FIBERS



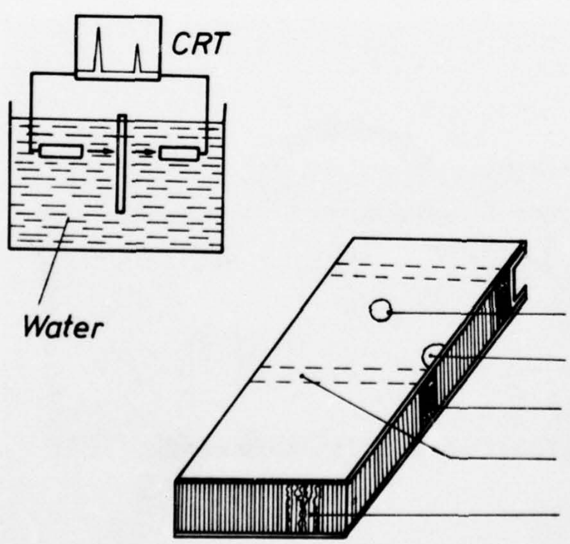
TEST RESULT
FOR LAMINATE

AREA	P[dB]
Scattering of good Bond	± 0,5
Porosity	2-6
Delamination	20-30
Cracks	—
Fiber Direction	—

$$P = 20 \lg \frac{Ag}{Aa}\ [dB]$$

Ag = CRT-Amplitude good Area
Aa = CRT-Amplitude other Area

Figure 11. TEST RESULTS for CFRP LAMINATES by US-IMMERSION THROUGH-TRANSMISSION



TEST RESULTS
FOR SANDWICH

AREA	P[dB]
Scattering of good Bond	± 1,5
Unbonds CFRP/Core	28
Unbonds CFRP/Core	22
Good Splice	14 – 17
Splice Flaw	8 – 11
Crushed Core	3 – 7

$$P = 20 \lg \frac{Ag}{Aa}\ [dB]$$

Ag = CRT Amplitude good Bonds
Aa = CRT Amplitude other Bonds

Figure 12. TEST RESULTS for SANDWICH by US-IMMERSION THROUGH-TRANSMISSION

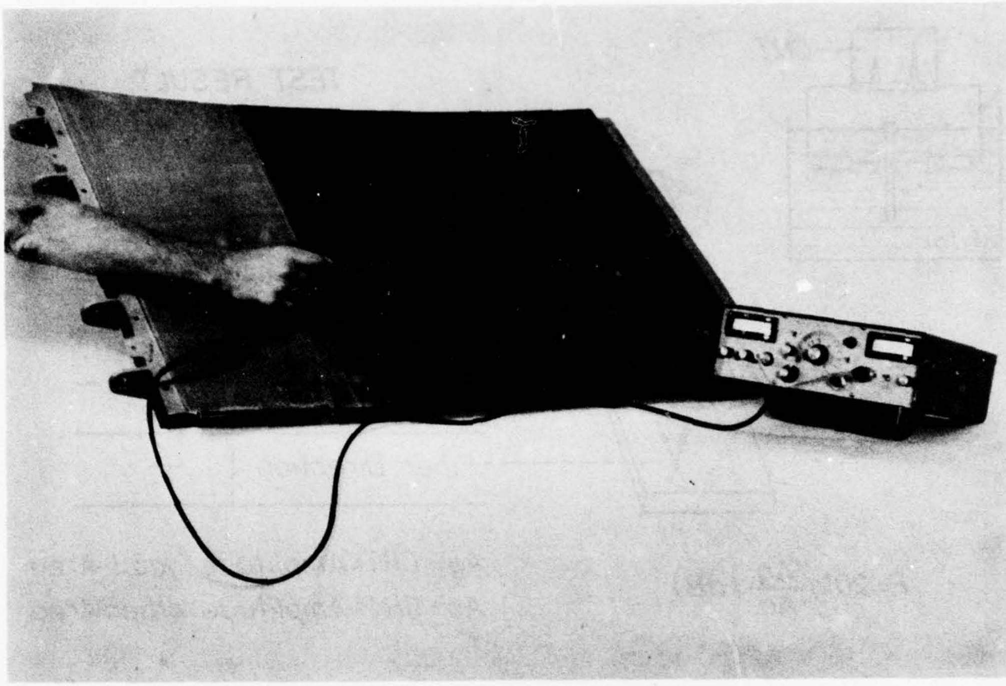


Figure 13. TEST with ACOUSTIC FLAW DETECTOR, OPERATING FREQUENCY 1-8 kHz (DOES NOT REQUIRE LIQUID COUPLANT)

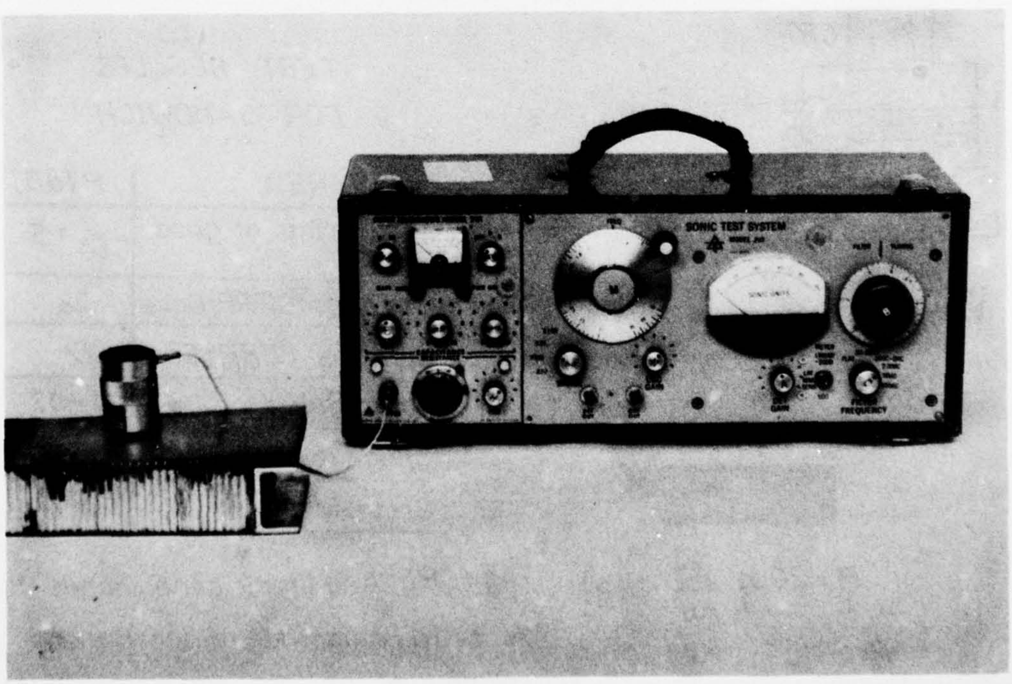


Figure 14. TEST with SONIC RESONATOR, OPERATING FREQUENCY > 15 kHz (DOES REQUIRE LIQUID COUPLANT)

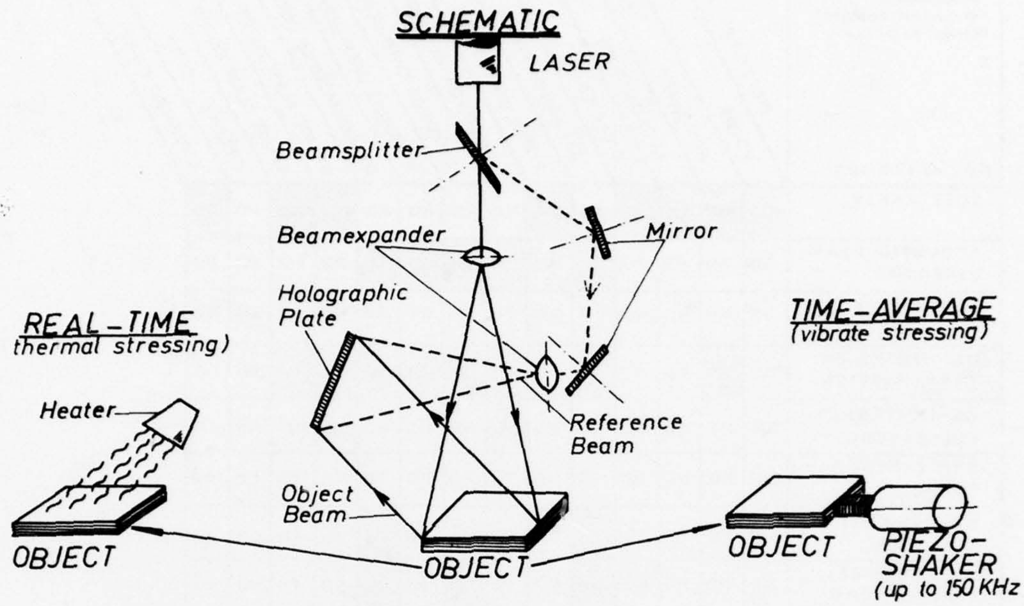
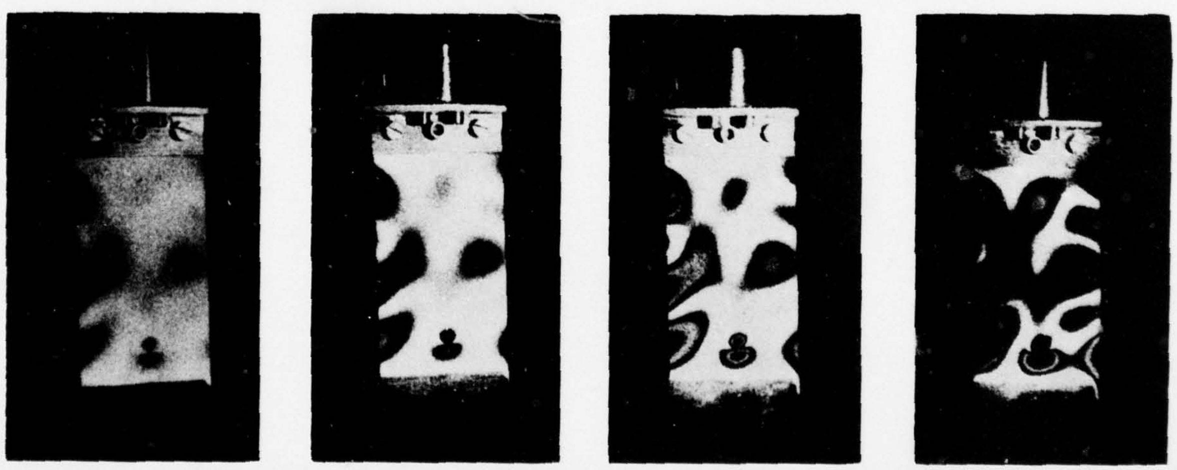


Figure 15. APPLIED TEST METHODS by INTERFEROMETRIC HOLOGRAPHY (HNDT)



U = 30 V U = 60 V U = 90 V U = 150 V

Figure 16. COMPARISON between FOUR HOLOGRAPHIC INTERFEROGRAMS by DIFFERENT VIBRATIONAL AMPLITUDES (U)
LAMINATE THICKNESS : 2 mm
VIBRATION FREQUENCY: 3.55 kHz
DELAMINATION DIA. : 20 mm
(TIME-AVERAGE, VIBRATE STRESSING)

GD=Good detected
D=Detected
PD=Partial detected
ND=Not detected

NDT-METHODS	LAMINATE: VOIDS	LAMINATE: POROSITY	LAMINATE: INCLUSIONS	LAMINATE: CRACKS	LAMINATE: DELAMINATIONS	LAMINATE: FIBER DIRECTION	ASSEMBLY: UNBONDS AL-CFRP	ASSEMBLY: UNBONDS CFRP-CORE	ASSEMBLY: UNBONDS CFRP-GFRP	ASSEMBLY: DELAMINATIONS CFRP	ASSEMBLY: SPLICE FLAW AL-CO	ASSEMBLY: SPLICE FLAW CO-CO	ASSEMBLY: CRACKS CFRP	ASSEMBLY: CRUSHED CORE
SOFT X-RAY	GD	GD	GD	D	ND	GD	ND	ND	ND	ND	GD	GD	PD	GD
ACOUSTIC FLAW DETECTOR	ND	PD	PD	PD	D	ND	D	D	D	D	PD	PD	PD	PD
TAPPING TEST	ND	ND	ND	ND	PD	ND	PD	PD	PD	PD	ND	PD	ND	ND
US-IMMERSION TRANSMISSION	ND	D	PD	ND	GD	ND	D	GD	GD	GD	D	D	ND	PD
US-IMMERSION PULSE-ECHO	ND	ND	PD	ND	PD	ND	D	ND	ND	ND	ND	ND	ND	ND
SONIC RESONATOR	ND	ND	ND	ND	PD	ND	PD	PD	PD	PD	ND	ND	ND	PD
HOLOGRAPHY REAL-TIME	ND	PD	PD	ND	D	ND	PD	PD	PD	D	PD	PD	ND	PD
HOLOGRAPHY TIME-AVERAGE	ND	ND	ND	ND	GD	ND	PD	D	PD	D	ND	PD	ND	PD

Figure 17. CORRELATION of NDT RESULTS for BUILT-IN DEFECTS

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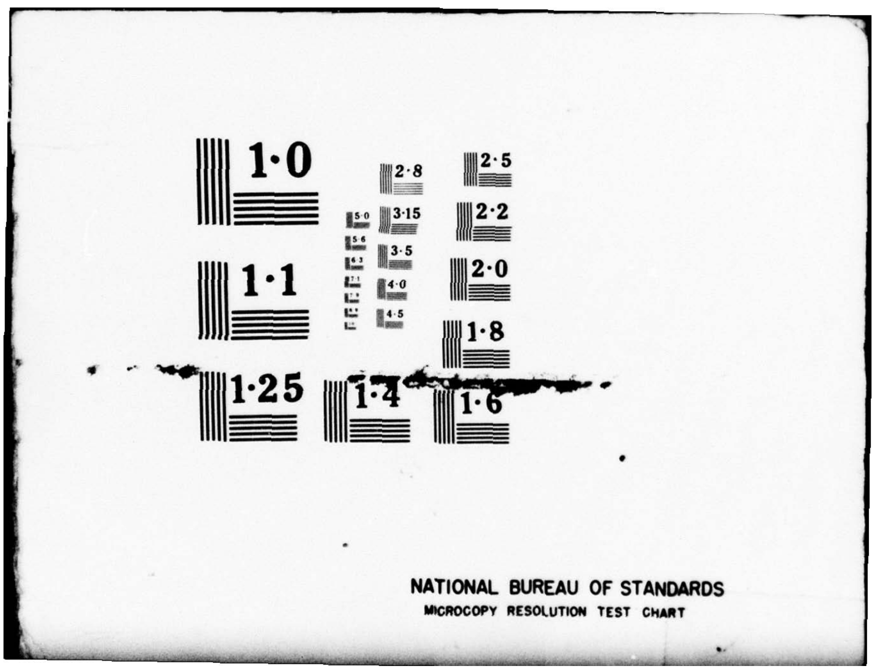
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5·0
NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

SESSION III
Part 1: Techniques
Rapporteur's Report

by

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1. SUMMARY OF PAPERS

The gratifying continuation of interest in the Nondestructive Inspection of fibre-reinforced composite materials is well attested by the three papers which have been received. These papers are all of widely differing kinds.

Mr Kaitatzidis of Dornier shows that suitably adapted techniques of X-radiography and ultrasonic pulse-echo or transmission attenuation are quite capable of assessing the acceptability of laminates and simple fabricated structures. Although he does not give details of the operating conditions of his testing equipment or the flaw criteria adopted for rejection, the results quoted are comparable with those in the literature. The importance of this work is that it is closely integrated with the manufacturing and operating programmes, and that repeated tests will be made systematically on items specially taken out of service over an extended period. There can be no real substitute for this direct empirical approach.

Mr Schliekelmann of Fokkers' has presented his current ideas about the application of his well-known Bond-tester to the problems of inspecting composite materials and structures. Significant points are that it is being used in important programmes not only at Fokker but also by Grumman and McDonnell Douglas NDI departments, and that it is regarded as essentially complementary to other techniques. This attitude is very reasonable: it is unlikely that a three-phase system (fibres-resin-pores) could be adequately inspected by a single technique. Just as the Bond Tester has often shown its value in the monitoring of adhesive quality in lap-joints, so it has been applied to the assessment of thickness, porosity and density in composite materials and bonded structures. Again, as in the case of the previous paper, the true value of the application will emerge when the extended test programmes on structures in service have been completed.

The paper by Dr Stone of Farnborough is concerned with the range of techniques available for the inspection of composites rather than with the testing of specific composite structures. There is no point in repeating the arguments in detail, especially as much of the work discussed has been published in detail elsewhere, but it is significant that the only techniques widely adopted for practical inspection of sheet material on the shop floor are variants of ultrasonics and X-radiography, as illustrated by the paper of Kaitatzidis. Stone's summary suggests that these techniques are already reasonably adequate for the inspection of fairly simple structures after fabrication and useful improvements are continuing. The problems which require most urgent attention are the quantitative evaluation of the significance of given defects, the inspection of complex structures including bonded parts and the study of the effects produced by service conditions of mechanical impact, fatigue and hydrothermal degradation. The lack of a device for testing adhesion bond strength is also a cause of embarrassment.

Finally, the paper by Tober and Schnell compares the detectability of various artificial manufacturing defects by a range of possible techniques, but again concludes that a judicious combination of soft X-radiography and ultrasonic C-scan gives the best overall coverage.

2. COMMENTS

There are two quite different approaches to the problem of NDI of CFRP. One may use well established techniques, as illustrated in this session, and apply them to fabricated structures as part of general flight testing. This approach has become possible only fairly recently, but it is analogous to the development of NDI for metal structures in the past. Alternatively we may attempt to link the NDI more closely with the scientific analysis of composite behaviour in terms of such studies as fracture mechanics and fatigue lifetimes. The first approach has the merit of practicality but could lead to serious errors and misunderstandings if unexpected modes of failure occur. The second approach has been under way for some time. It requires close collaboration between NDI staff and other sections responsible for fabrication and

mechanical testing. Yet the mechanical significance of particular defects remains obscure in general and there is a danger here of devoting too much effort to the elucidation of insignificant problems. It is also a field in which it is difficult to preserve scientific rigour. Thus there is much information in the literature about the smallest defects detected by a given technique, but very little about the largest defects which remained undetected and which are just as important from the user's point of view.

A focal point in this work is the investigation of shear properties. A recent paper by Hancox (1977) has now given some quantitative indication of the effects of flaws and voids on shear stiffness and strength in CFRP rods and tubes. The effects of matrix voids on the velocity of propagation of ultrasonic waves can now be calculated with precision. There is thus a prospect of a really useful relationship being established between ultrasonic tests and shear strength which bears on flexural and compressive behaviour.

Shear properties are also of vital interest in fatigue damage, as was made clear at a recent conference on the subject organised by the Society of Environmental Engineers (1977). Uniaxial CFRP is remarkably resistant to tensile fatigue, but severe degradation is caused by off-axis or shear stresses. Analysis of such results will be necessary in the assessment of fatigue damage in complex laminates. In particular, short-beam shear test results are not adequate for this purpose.

3. CONCLUSIONS

It seems that the time is now ripe for a more down to earth empirical approach to the NDI of composite materials. Although this has its dangers, the advances in fabrication technology and theoretical background probably justify some slight risks. Some of the more advanced techniques advocated in the past, such as optical holography and acoustic emission have not so far justified the extra effort and expense they would incur.

There is, however, a definite need for making the applications quicker and cheaper. All improvements in ultrasonic transducer quality, scanning techniques and low-voltage radiography should be carefully assessed for applicability to composites.

Finally it should be emphasised that substantial advances in the subject are most likely to be made by the adoption of integrated programmes in which the NDI is carried out as an essential part of the other studies of, for example, fracture mechanics, fatigue or hydrothermal degradation. The nondestructive tests must be carried out on the specimens studied by other methods in these programmes.

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Hancox, N.L. J. Materials Science 12, pp.884-892, 1977.

— *Fatigue of Fibre Reinforced Composites*. Society of Environmental Engineers, Fatigue Group, 1977.

DISCUSSION SUMMARY
Session III – Part 1

J.Quinn (UK)

There is a dramatic increase in laminate thickness in prospect in the near future. In the UK an order of magnitude increase from 5 mm to 50 mm in laminate thickness is expected. I would like to ask whether anyone has any experience of NDI on laminates of this thickness, and whether they anticipate any new problems in their examination.

G.Jube (FR – Session Chairman)

I think your question is very pertinent because we must concentrate on NDI methods at a very early state of the development of composites. Up to the present these materials have been used only for secondary structures, but the high cost of materials means that the weight saving will only have significance if they are used for primary structures. In the future we will not only produce very thin parts (as has been the case up to now) but we shall need to produce very thick parts such as wing skins, and that is the problem on which we must concentrate. I do not feel that checking the quality of sandwich skins 1 or 2 mm thick will pose a severe problem, but I am concerned with the application of these techniques to thick laminates.

W.N.Reynolds (UK)

Mr Schliekelmann compares his measurements with the Fokker bond tester with conventional C-scan ultrasonic measurements. He says that the measurements with the Fokker instrument depend basically on the elastic modulus, and changes in the modulus can be interpreted in terms of changes in porosity concentration. Information of both the attenuation and the elastic modulus are available from the C-scan signal, so that one can measure both the attenuation and the time delay on the same pulse. Would this not eliminate the necessity of using the Fokker bond tester?

R.J.Schliekelmann (NE)

The experience of our American friends, who have well-developed C-scan systems available, is that the ultrasonic signal is scattered by the presence of the voids and so the real dimensions of the voids are not accurately defined by the C-scan. For this reason they use the resonance technique in order to define more precisely the size of the defect.

With regard to the reliability of holography, naturally for holographic interference interpretation there needs to be a large amount of experience and training as is the case for all other kinds of NDI. Our experience with the system for production inspection over the past 7 years on light sandwich structures has shown that the system is revealing not only the slight defects in the adhesive layer but also things which might otherwise never be seen, such as slight inaccuracies in the machining on honeycomb core and node bond troubles in the honeycomb.

Using the holographic interference system enables us in a matter of 30 minutes to judge the soundness of a large adhesive bonded or composite component.

D.E.W.Stone (UK)

I would not disagree with you, but it would be useful if there was a means of de-sensitising the technique from time to time so that only major defects could be revealed.

J.R.Lee (UK)

I would like to raise the question of the cost of the NDI of composites. Listening to a description of the wide range of processes that are being used, and knowing that many of them are still in operation, it seems to me that the cost of NDI on a complex composite structure must contribute significantly to the total cost of the component, particularly in comparison with the metallic component which it is replacing. I believe that the enthusiast for composites often neglects this cost when making his comparison with the alternative metallic structure. I wonder if any of the manufacturers of production parts could give us an indication of the percentage of the cost which is taken up by NDI.

M.Kaitatzidis (GE)

We are manufacturing a composite airbrake and the cost of the NDI is about 15% of the manufacturing cost. For the original aluminium airbrake the NDI cost was about 7%.

K.O.Sippel (GE)

Mr Schliekelmann showed a very large component approximately 1 m by 6 m which was tested by holographic means. I would like to ask whether the testing was done in the laboratory or whether it is the intention to introduce this method in the normal manufacturing process?

R.J.Schliekelmann (NE)

The installation has been used as a full scale production testing unit at the pre-production stage of very complex sandwich components. After the difficulties of its introduction were overcome, the cost which was involved in using this holographic technique was seen as no longer necessary, and the installation is now used only for those cases where the alternative methods show questionable results. One of the drawbacks of the system is its sensitivity to foreign vibrations.

T.Sharples (UK)

In Wing Commander Kent's paper the designers were warned to be aware of the need for NDI in the future, especially since damage tolerant designs will be very firm requirements for new aircraft. If we accept that carbon fibre will be the material of the future, and if we believe Dr Stone's comments that there is little chance of being able to detect the ingress of moisture which is likely to be very damaging to adhesive bonds, then the designer must react in some way. Their approach could be to allow for the maximum possible flaws in critical areas and conduct enough tests on representative structures containing these flaws to ensure adequate service life and, of course, ensure that during manufacture the flaws were not greater than those assumed.

D.E.Stone (UK)

I am not sure that I can comment, but I certainly want to correct the initial statement. I did not say that there was very little chance of detecting moisture ingress. I said that despite the amount of work which has gone into the materials investigations for moisture ingress there was very little NDI element in this work. I think that is reprehensible. I believe there are several possibilities for detecting moisture ingress, and I hope that the RAE will be making its own contribution to this topic.

G.C.Deutsch (US)

I would like to make a philosophical comment, and I am not really sure whether it concerns NDI or quality control. Everything I have heard said at this meeting seems to be aimed at discovering discontinuities in a manufactured structure, but I have heard nothing about inspections which may reveal the degree of polymerisation of the resin or the degree to which the bond is of high quality. It seems to me that we are rapidly approaching the time when we must say not only that a component is free of discontinuities, but that the component will last for 50000 hours. We should be paying more attention to this aspect.

G.Jube (FR – Session Chairman)

The methods which involve a measurement of the modulus might give an operational answer to your problem, particularly in so far as the degree of polymerisation is concerned.

I have a preoccupation regarding the qualification of people who use the devices which have been described at this meeting. The indications given by devices which measure modulus are very subjective. There is not a clear "yes or no" answer from the equipment, and this poses a problem regarding the qualification of the operator.

I understand that in some countries inspectors are being qualified at various levels and the controller of the various levels is called on to decide if any indication can be interpreted as a serious defect. This is a human aspect which seems very important to me.

G.A.Darcy (US)

The US Army has just entered into a certification programme for its technicians at levels 1, 2, and 3. The highest level (level 3) will be in charge at the various military bases and will oversee the establishment of tests and the certification of technicians at the lower levels. We are also giving preliminary thought to the establishment of a level 4 for professional engineers.

J.Mar (US)

It seems to me that NDI experts, instead of obtaining more and more sophisticated information that requires training of specialists, should concentrate their efforts on automation. If people are clever enough to be specialists in evaluating C-scan output, for example, then I submit that they will get bored very quickly, and it is well nigh impossible to expect the same man to be looking for the same thing day after day with the same level of success. At one USAF base, inspectors have the tedious task of looking for cracks in the fan blades of an engine. The Commander of the base offered an all-expenses-paid weekend at Las Vegas for anyone who found a crack. But after a very few days he gave up the idea because nobody found anything. Even with this incentive they could not keep the inspectors' interest in looking for flaws that occurred only once in every 10000 blades.

G.Jube (FR – Session Chairman)

You are right in believing that automation is the ultimate answer to the problem, and we are still far from attaining this goal. We still have to fly aircraft manually, and it will be a long time before they are automatically controlled.

D.M.Forney (US)

There is a standing difficulty in choosing who should be an inspector and who should not. There seems to be very little effort to determine whether Mr Smith should be an inspector at all, even if he passes the initial qualification test. A colleague of mine made an observation one day that he thinks the best inspector would be a person who

loves to fish and does not care if he catches anything or not. He needs that sort of patience and serenity in his makeup. I doubt if any of us have the time to consider a project to solve this problem.

There is a programme (which is about 75% complete) in the USAF in which we are taking around various bases in the USA a variety of aircraft structural parts which have been returned because they are full of fatigue cracks initiated during normal operation. We have taken these pieces of structure apart very carefully, and to the best of our ability identified where the cracks exist and what is their surface length. We have reconstructed the parts and painted them to make them look like regular parts which have never been dismantled. We have used these to test our field inspectors on a day-to-day basis. The results of this supposedly clandestine (but very well known) test of these inspectors indicates that even though they know they are being tested, the results are less than good. Part of the problem is that we do not really know who we should assign to the task of inspection. Some of our data tells us that the length of training dictates the quality of the results, but if you plot the probability of detection against the number of hours of specialised training you get the pattern which you would get if you fired a shotgun at the paper. So it must be something in addition to these factors which makes a good inspector, but we do not have a place on our questionnaire to ask "Do you love to fish and do you care if you don't catch anything?" We talk glibly about the accuracy of our techniques carefully measured in the laboratory, but we really are not paying enough attention to how much loss of accuracy we have to endure when we hand it to our field technicians. As a group of NDI people we should pay some attention to the psychological factors which must be involved in making a successful and reliable technician. If we can pay more attention to these human factors and reduce his subjective impact on the answer, we may make the gains for which we should be striving.

T.Gaymann (GE)

Our experience is that there are certain types of people who are fit to be inspectors. They are not people who are very clever, and I accept that you have to watch the psychological environment, but you also have to make the job very attractive. My second point is that you should not try to push these people for an engineering type of interpretation, which is the point Professor Mar was making. I think you have to have inspectors who find abnormalities, but you need someone else to make the interpretation. You cannot combine both abilities in one person.

A.R.Bond (UK)

This is the point which I was making in the last session. If you are going to ask people to make very detailed inspections and give them powers of decision, then you have got to use people with more and more logic. I was using education as a measure of the power of logic. In the USAF exercise no account was taken of the education of the man, and the point I wish to make is that either the inspection process has to be automated or a more highly educated inspector has to be used. What we have done is to add peripheral training programmes so that the man does not just do a particular job but has an interest in the structure around about. He is in contact with the manufacturers and he takes an interest in the general area, not just in a particular bolt hole.

I.M.Matay (US)

I agree that this is a problem of human nature. You can improve on it by selecting the best men and providing attractive conditions, wages, education and so on. However, the increased percentage of parts requiring close inspection and the introduction of composite materials dictate automation, and many of us believe that the field of electonics will come to our aid. I disagree with my British colleagues who put the accent on investment of more highly educated operators rather than on machines.

G.Jube (FR – Session Chairman)

The discussion has reached a very high human level, and we can sum it up by saying that we cannot avoid using human capacities for quality control for a long time to come. On the other hand, we must use every possible technique to relieve the operator from the boring part of his work, and help him to avoid making errors due to fatigue and the routine nature of his job.

ETAT ACTUEL ET EVOLUTION EN FRANCE
DU CONTROLE DE STRUCTURES D'AVION EN COMPOSITES CARBONE

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RESUME

Un certain nombre de méthodes de contrôle non destructif utilisables pour le contrôle des structures d'avion en composites sont passées en revue. Ces méthodes sont actuellement, soit en cours d'évaluation, soit déjà utilisées industriellement. Parmi ces méthodes, celle qui semble le mieux adaptée au contrôle des revêtements monolithiques est le contrôle par ultrasons en transmission avec enregistrement type C. Pour le contrôle des structures sandwichs, l'interférométrie holographique parait être la méthode globale qui devrait déboucher sur une utilisation industrielle.

D'autres méthodes peuvent également être utilisées en complément pour des contrôles ponctuels.

1 - INTRODUCTION

Le développement de l'emploi des composites dans les structures d'avions et en particulier des sandwichs à revêtements en fibres de carbone et âmes nids d'abeilles conduit à revoir le problème du contrôle non destructif afin de l'adapter à ces matériaux nouveaux.

Les structures avions que nous avons à contrôler sont essentiellement constituées de revêtements en fibres de carbone , intégrés dans des assemblages réalisés par collage et notamment des structures composites sandwichs telles que panneaux sous train, Karmans, dérives etc.....

Le contrôle final sera effectué sur l'élément terminé d'assemblage mais généralement l'on procède à des contrôles intermédiaires à différents stades de la fabrication. C'est ainsi que l'on examinera tout d'abord les revêtements afin de rechercher des défauts internes, puis les assemblages de la structure terminée.

Parmi la panoplie des méthodes existantes nous allons passer en revue celles qui ont donné les meilleurs résultats au cours de nos essais.

2 - PIECES A CONTROLER

2.1 - Composition d'un revêtement (Carbone-résine)et défauts recherchés

Un revêtement est composé d'un certain nombre de plis imprégnés de résine. Les plis sont drapés de façon variable et chaque pli a une épaisseur de 0,125 mm environ.

Les principaux défauts pouvant affecter les revêtements sont les porosités, les délaminages, les inclusions (oubli de séparateurs par exemple), les chevauchements de plis ou les absences locales de plis (mauvais raboutages).

2.2 - Composition d'une structure sandwich et défauts recherchés

Les structures sandwichs dont il est question ici sont constituées essentiellement de revêtements carbone et d'âme en nida non métallique (NOMEX). Les bordures sont en titane.

L'assemblage est réalisé par collage des divers éléments constitutifs.

Les défauts susceptibles d'être rencontrés sont de 3 types :

- défauts dans les revêtements : ces derniers ayant déjà été contrôlés avant assemblage, on ne recherche à ce stade que les défauts apparus pendant l'assemblage (essentiellement des délaminages)
- les défauts de collage aux différents niveaux :
  - . revêtements- Nomex
  - . revêtements- Titane
  - . Titane - Nomex
- les défauts dans l'âme Nomex (déformations, déplacements)

Le contrôle des sandwichs carbone-epoxy-nomex pose des problèmes très spécifiques à ce type de structure, structure s'apparentant cependant aux sandwichs à peaux et âmes métalliques.

Cette spécificité provient de la nature hétérogène des peaux , de leur grande rigidité, ainsi que du grand coefficient d'amortissement ultrasonore de l'âme Nomex.

Parmi toutes les méthodes disponibles, nous avons retenu quatre d'entre elles qui donnaient les meilleurs résultats sur nos structures :

- la radiographie
- les ultrasons
- les méthodes soniques
- l'holographie

3 - METHODES DE CONTROLE

3.1 - Contrôle ultrason par transmission

La méthode la plus utilisée pour le contrôle des revêtements monolithiques, celle qui donne le maximum d'informations sur la santé du matériau est la méthode ultrasons par transmission avec enregistrement type C (C-Scan)

Principe de la méthode

Lorsqu'un faisceau ultrasonore traversant un composite rencontre un défaut, la partie du faisceau interceptée par le défaut est réfléchie et renvoyée en partie vers le palpeur,la partie du faisceau non interceptée par le défaut continue son chemin et traverse complètement le composite.

La détection d'un défaut peut donc se faire, soit en analysant les échos réfléchis, soit en étudiant la diminution d'amplitude du faisceau transmis. C'est cette dernière méthode qui est décrite ici et que nous utilisons pour le contrôle des revêtements. Elle présente l'avantage de permettre le contrôle du revêtement sur toute son épaisseur (même lorsque cette épaisseur est faible) alors que la méthode par réflexion laisse subsister des zones mortes non contrôlées. De plus, la méthode par transmission se prête très bien au contrôle automatique avec enregistrement.

Le signal reçu après simple ou double transmission dans le matériau est analysé et une cartographie est effectuée, le noircissement du papier étant fonction de l'amplitude du signal.

Appareillage utilisé

L'installation utilisée pour ces contrôles comprend :

- une cuve remplie d'eau au fond de laquelle se trouve une plaque de verre jouant le rôle de réflecteur,
- un système de balayage permettant le déplacement du palpeur suivant deux axes X et Y
- un système d'enregistrement par brûlage de papier. Cet enregistrement s'effectue par niveaux : 6 niveaux de gris (allant du blanc au noir) sont obtenus suivant l'amplitude du signal recueilli,
- palpeur ultrasons émetteur-récepteur
- appareillage ultrason équipé d'un voltmètre digital permettant des mesures locales d'atténuation ultrasonore précises.

Principes de l'absorption dans le composite

Le faisceau d'ultrasons émis par le palpeur traverse le composite, se réfléchit sur la plaque de verre et après une deuxième traversée du composite revient vers le palpeur qui joue à ce moment le rôle de récepteur. A chaque traversée d'interface (interface eau-composite et composite eau, réflexion sur le verre) une partie de l'énergie est perdue.

En fait, la mesure de l'atténuation se fait sur l'écho correspondant au retour du faisceau après réflexion sur le verre en comparant l'écho recueilli sans composite et l'écho obtenu après interposition du composite. Dans ces conditions, l'atténuation dans l'eau et les pertes par transmission dans le verre s'annulent.

Il reste donc :

- l'atténuation due aux réflexions aux interfaces
- l'absorption dans le composite
- l'absorption due aux défauts éventuels

Avec une fréquence de 5 MHz un faisceau focalisé à 50 mm et un diamètre de faisceau de 3mm, la courbe d'étalonnage d'un composite carbone-résine peut s'écrire avec une précision suffisante :

$$A_{dB} = K_1 + n\,K_2 - 20\,K_3\,(\,n-1\,)\,\log\,(\,1-C)$$

avec A_{dB} = Atténuation pour un double parcours entre un trajet dans l'eau sans composite et le même trajet avec composite.

K_1 = Atténuation aux interfaces + états de surface

K_2 = Atténuation intrinsèque

n = Nombre de plis

C = Taux de porosité

K_3 = Facteur de forme

Influence du palpeur ultrasonore

Le type de palpeur utilisé a une grande importance sur les courbes d'étalonnage.

L'absorption dépend de la fréquence, mais la caractéristique la plus importante du palpeur est la géométrie du faisceau et notamment le diamètre dans la partie active (trajets dans le composite).

Pour nos structures, nous utilisons un faisceau de diamètre 3mm (compromis entre définition et sensibilité). Un tel diamètre d'autre part, n'est pas trop sensible à l'état de surface, ce qui n'est pas forcément le cas avec des faisceaux plus pontuels.

Résultats obtenus

La plupart des défauts (tels que délaminages) présents dans les revêtements apparaissent de façon claire sur les enregistrements. Par contre, la porosité peut varier de façon progressive depuis un taux très faible jusqu'à des porosités très importantes. Il a donc été nécessaire, afin de pouvoir étalonner la méthode, d'effectuer des enregistrements ultrasonores sur un grand nombre d'éprouvettes (éprouvettes de réception, étude des différents paramètres de fabrication, etc....) afin de pouvoir relier les atténuations ultrasonores au taux de porosité du matériau et aux caractéristiques mécaniques. Les faibles taux de porosité n'ont pas d'influence notable sur les caractéristiques mécaniques. Par contre, dès que l'on dépasse quelques %, les caractéristiques chutent rapidement et d'autre part la tenue au vieillissement risque d'être fortement affectée. Actuellement, nous disposons de courbes de corrélation entre amortissement ultrasonore et taux de porosité et les critères d'acceptation sont définis en étroite collaboration avec les Bureaux d'Etudes.

Cette méthode ultrasonore pour double transmission avec enregistrement type C est la méthode de base pour le contrôle des revêtements.

3 2 - Contrôle ultrason par réflexion

Comme nous l'avons vu précédemment, le contrôle d'un composite peut s'effectuer en examinant les échos réfléchis par les défauts.

Cette méthode présente, par rapport à la précédente, l'inconvénient de laisser subsister des zones non contrôlées (zones mortes) près des faces d'entrée et de sortie. Par contre, elle ne nécessite que l'accès d'un seul côté et se prête ainsi parfaitement bien au contrôle sur structure assemblée terminée (contrôle en maintenance notamment) ainsi que dans le cas de structures à raidisseurs intégrés.

Du fait des faibles épaisseurs des composites, il est nécessaire d'obtenir des zones mortes les plus faibles possibles. Ceci peut être obtenu en utilisant :

- un émetteur-récepteur d'ultrasons à très haute résolution
- une fréquence relativement élevée (10 MHz)
- une base de temps suffisamment rapide pour étaler sur l'écran toute l'épaisseur du composite

La technique par réflexion peut être utilisée soit en immersion avec enregistrement de type C (C-Scan) soit par contact.

L'immersion ne s'avère en fait interessante que pour les composites de forte épaisseur du fait de la difficulté de synchroniser parfaitement le créneau à l'intérieur du composite (accroissement de la zone morte).

La méthode par contact donne des zones mortes de l'ordre de 0,5mm près de la face d'entrée et de 0,3mm près de la face de sortie. C'est une méthode souple, ne nécessitant pas d'appareillage compliqué. Elle est parfaitement adaptée au contrôle en maintenance et permet par exemple le suivi du contour d'un défaut.

3 3 - Courants de Foucault

Les propriétés électriques des matériaux composites sont tout à fait différentes de celles des métaux Il s'agit en fait dans le cas des fibres de carbone, d'une matrice non conductrice renforcée avec des fibres conductrices C.N. OWSTON (1) a montré que les défauts modifiaient localement les propriétés électriques du matériau et qu'ils pouvaient ainsi être détectés à condition d'utiliser des fréquences suffisamment élevées

Nous avons,en utilisant cette méthode, mis en évidence des oublis de séparateur dans un revêtement monolithique de 4 plis avec accessibilité d'un seul côté Aucune autre méthode ne nous avait permis de détecter ce défaut.

3.4 - Radiographie

La radiographie est utilisable aussi bien pour le contrôle des monolithiques que des assemblages sandwichs. Pour le contrôle des revêtements monolithiques, on utilise la radiographie basse tension et l'on peut détecter les défauts suivants :

- manque local d'un pli
- écartement local des fibres dans un pli
- chevauchement de nappes
- raboutage
- écartement de mèches
- hétérogénéité de taux de résine
- inclusions métalliques
- oubli de séparateur

La détection des défauts cités ci-dessus est d'autant meilleure que le nombre de plis est faible. En ce qui concerne les structures sandwichs nids d'abeilles, la radiographie est utilisée pour la détection des défauts de l'âme NOMEX (déformations, accostage Nomex-bordures, positionnement d'inserts, ruptures de nids d'abeilles, etc....

3.5 - Holographie

L'interférométrie holographique puisqu'elle permet la détection de légers déplacements de la surface d'un objet, est donc capable de détecter des défauts dans les joints collés ou des délaminages dans le revêtement. Le contrôle de structures avion par cette méthode a déjà été effectué avec succès, notamment par FOKKER Hollande (2).

Nous avons effectué des essais en laboratoire afin de déterminer les modalités d'application de la méthode à nos structures. Les résultats se sont révélés très prometteurs , notamment en ce qui concerne le contrôle des sandwichs nids d'abeilles et ont abouti à la réalisation d'une installation pour le contrôle des pales d'hélicoptères. Pour cette installation, le mode de contrainte qui s'est révélé le plus intéressant est la dépression, la pale ou un tronçon de pale étant placée dans un caisson à dépression.

D'autres essais de laboratoire sont également effectués afin d'étudier les possibilités de mise sous contrainte par vibration avec analyse en temps moyenné. Le contrôle par interférométrie holographique nous semble dès à présent applicable à un certain nombre de structures en utilisant un laser continu. L'utilisation de lasers pulsés qui permet de s'affranchir d'installations encombrantes est également en cours d'étude, l'utilisation de tels lasers s'avérant intéressante pour le contrôle de pièces de grandes dimensions et pour des contrôles in situ.

L'holographie est une méthode très sensible qui permet de détecter des défauts de petites dimensions (surtout dans le cas des revêtements minces). La définition des critères d'acceptation nécessite de nombreux essais en collaboration étroite avec les Bureaux d'Etudes.

3.6 - Ultrasons pour le contrôle des joints collés

Pour le contrôle des joints collés (monolithique/monolithique , monolithique/métal, monolithique/nid d'abeilles Nomex) ont peut également utiliser les ultrasons tels qu'ils sont utilisés sur les structures métalliques, c'est à dire en examinant la courbe enveloppe des échos multiples provoqués par le joint de colle.

Cette méthode présente l'avantage d'être simple et facile à mettre en oeuvre.

3.7 - Autres méthodes

Un certain nombre d'autres méthodes sont également utilisées en complément des méthodes précédentes. Ce sont notamment :

Fokker Bond Tester

Sonic Resonator

Sondicator

4 - CONCLUSIONS

Nous venons de passer en revue un certain nombre des méthodes utilisables pour le contrôle des composites en fibre de carbone. Parmi ces méthodes, certaines sont déjà utilisées de façon industrielle, d'autres sont encore au stade recherche en laboratoire. Pour chaque type de structure il est intéressant de pouvoir disposer de plusieurs méthodes qui puissent se compléter. Par exemple, pour le contrôle des revêtements monolithiques, la méthode de base est le contrôle par ultrasons en transmission avec enregistrement type C. Cette méthode, globale, fournit des renseignements très intéressants. Elle peut être complétée ponctuellement par d'autres méthodes telles que ultrasons par réflexion, radiographie ou courants de Foucault.

Pour le contrôle des structures sandwichs ou autres joints collés, nous pensons que l'holographie devrait pouvoir jouer le rôle de méthode globale .

Il est donc nécessaire de poursuivre les essais d'évaluation des différentes méthodes afin de pouvoir définir pour chaque cas particulier, la ou les méthodes à retenir.

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C·SCAN (DOUBLE TRANSMISSION)

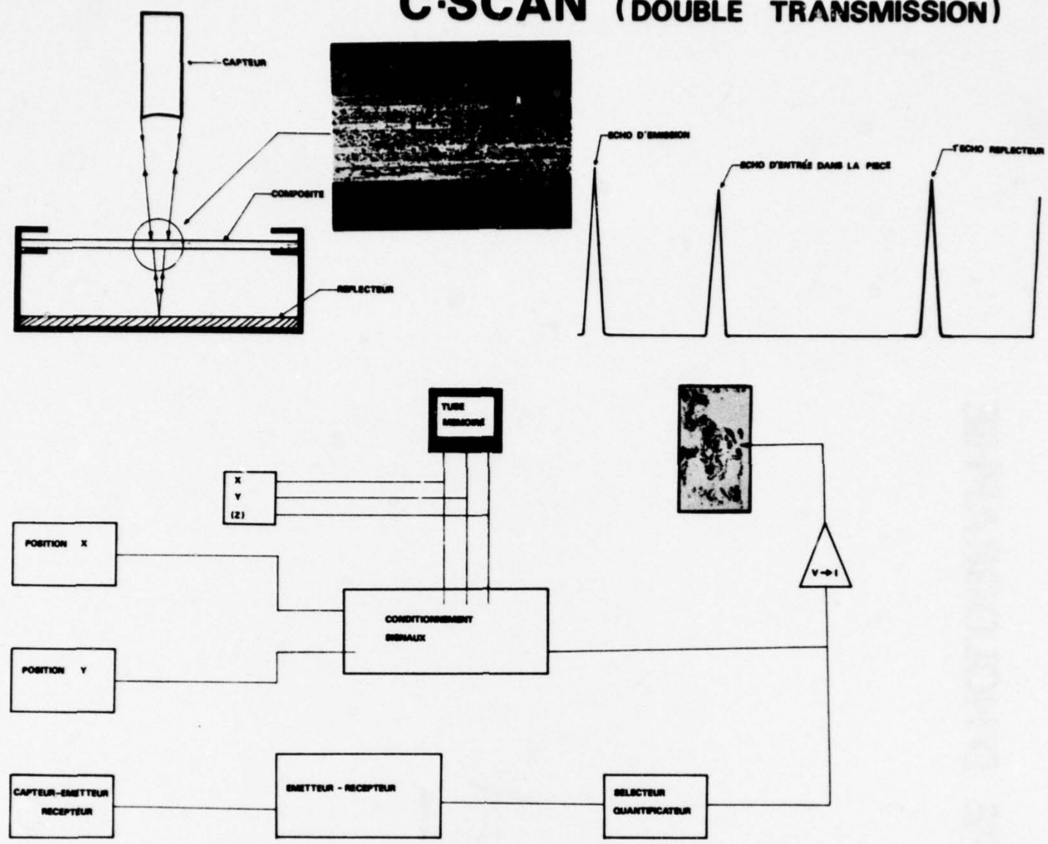

FIGURE n°1

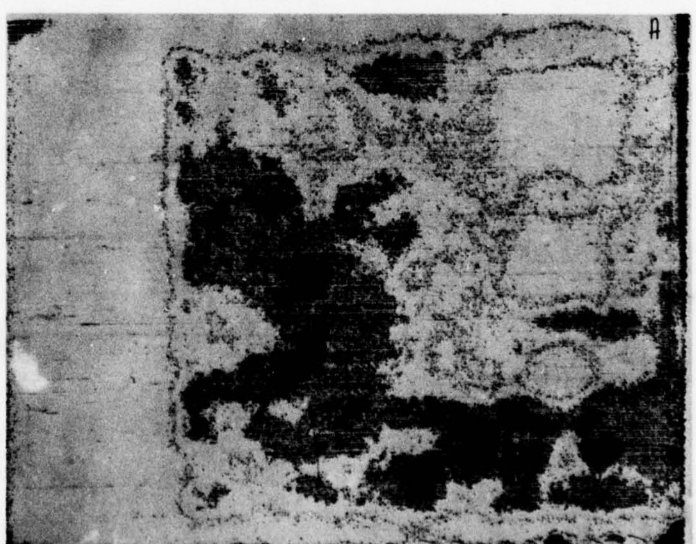

FIGURE n°2

Enregistrement type C plaque défectueuse

SCHEMA PRINCIPE D'HOLOGRAPHIE

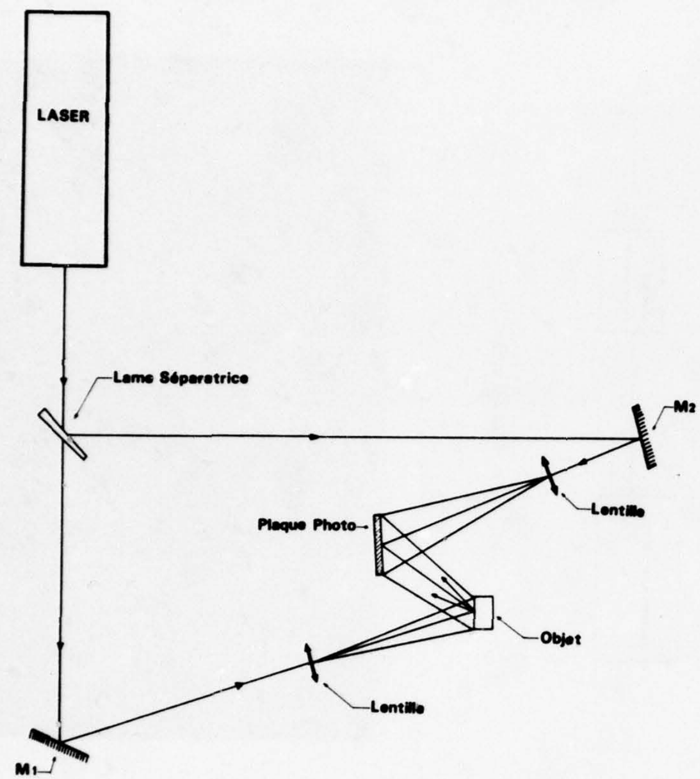

FIGURE n° 3

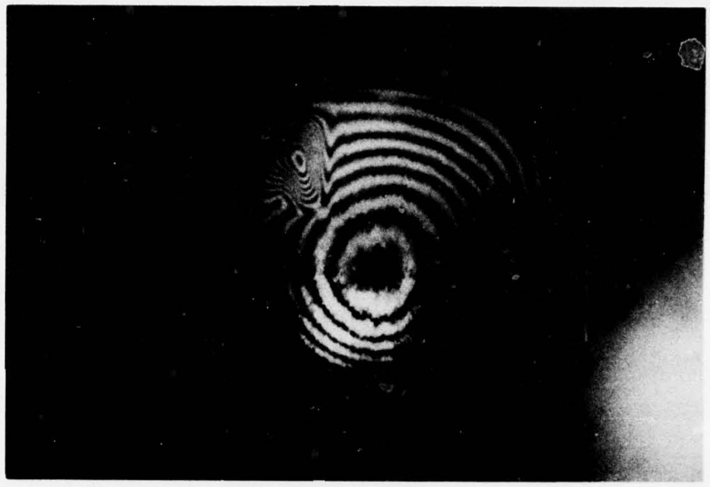

FIGURE n° 4

Hologramme sandwich carbone-Nomex
- Revêtement carbone-résine 4 plis
- Dimensions éprouvettes 30 x 30 cm
- Dimensions défaut 5 x 5 cm
- Sollicitation : chauffage

FIGURE n°5

Hologramme sandwich carbone-résine
- revêtement carbone-résine 4 plis
- dimensions défauts 50 x 50 mm et 25 x 25 mm
- sollicitation : dépression

CONTROLE NON-DESTRUCTIF DES STRUCTURES BOBINEES ET RECEPTION DES MATIERES PREMIERES

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RESUME :

Actuellement la fiabilité des structures bobinées, notamment celles des propulseurs à propergol solide est assurée par :

- le contrôle réception des matériaux qui repose sur les essais mécaniques conventionnels associés à des contrôles physiques et chimiques (spectrographie infra-rouge microcalorimétrie, etc...) pour vérifier le niveau de péremption et le vieillissement des matières organiques,

- le contrôle non-destructif des sous-ensembles et des structures complètes qui comprend deux phases : la détection globale par thermographie infra-rouge suivie de la caractérisation de défaut par ultra-sons et les rayons X.

Nos efforts de poursuite en matière de contrôle inspection sont orientés dans les deux directions suivantes :

- élargissement du champ exploratoire des moyens : C.N.D. : Etude de l'introduction de l'holographie et de l'analyse acoustique,

- amélioration des techniques physico-chimiques pour une meilleure évaluation des durées de vie des matériaux organiques.

PLAN DE L'EXPOSE

1. INTRODUCTION

L'Etablissement Aquitaine de l'Aérospatiale - Division Balistique et Spatiale est spécialisé dans l'étude et la réalisation de structures d'engin en matériaux composites.

Ces structures d'engin très sollicitées en contraintes mécaniques et thermiques nous obligent à la course permanente aux performances massiques. Notons qu'en ce qui concerne les caractéristiques mécaniques, le coefficient de sécurité admis a été limité à 1,4.

Pour assurer le maintien d'un niveau de fiabilité élevé, il a été nécessaire d'instituer un dispositif de Contrôle Qualité à tous les niveaux de la réalisation des structures d'engins, depuis la réception des matières premières jusqu'au stade final de la structure avant livraison.

Nous nous proposons de schématiser l'état actuel de ces aspects du Contrôle Qualité et ensuite de donner un aperçu de leur évolution future en fonction des recherches en cours et des moyens récemment apparus sur le marché.

2. LE CONTROLE RECEPTION DES MATIERES PREMIERES

2.1 Base du Contrôle Réception

Après qu'un matériau composite ait été évalué et caractérisé, par le laboratoire matériau qui officialise son introduction dans la chaîne industrielle de fabrication par des spécifications techniques, il est l'objet de contrôles de réception définis par des instructions de contrôle usine (I.C.U.).

2.1.1 Catégories de produits à contrôler

Les constituants des différents matériaux se répartissent approximativement dans les catégories suivantes :

(1) - Les résines (Epoxy - phénoliques - silicones - imides)

- les réactifs et durcisseurs correspondants,

- les solvants,

(2) - les fibres et tissus secs (non imprégnés) (verre silice carbone Kevlar...)

(3) - les matériaux préimprégnés le plus généralement de résines époxy ou phénoliques

(4) - Les colles, films de colles et adhésifs,

(5) - les caoutchoucs

2.1.2 Paramètres à contrôler

La nature organique de la majorité de ces produits nécessite la surveillance de paramètres physico-chimiques en plus de celle des caractéristiques "mécaniques ou thermiques opérationnelles" qui sont directement liées à l'aspect fonctionnel de l'utilisation.

Nous avons résumé dans le tableau n°1 ci-après, les principaux paramètres à surveiller en fonction des grandes classes de matériaux définies plus haut.

En ce qui concerne les contrôles mécaniques, il n'y a pas de problèmes particuliers, les processus, sans être définitivement figés ne connaîtront guère d'évolution. Ils font d'ailleurs pour la plupart, l'objet de normes.

L'essai hydraulique de "mini capacités" qui donne les caractéristiques pratiques bidirectionnelles du composite n'est pas encore normalisé, mais il est à noter que le fabricant de la fibre nous a suivi dans l'emploi de ce type d'évaluation.

Pour les contrôles physico-chimiques, on se limite actuellement à vérifier la conformité chimique de certains produits (des résines et certaines colles). On utilise un banc de spectrographie infra-rouge qui traduit sous forme de diagramme l'absorption dans diverses valeurs de longueurs d'onde suivant les fonctions chimiques (OH, NH, CO...). On se borne à vérifier qualitativement la présence des principaux pics en se référant à un diagramme étalon.

Dernièrement, il a été possible, dans une colle, de détecter la présence anormale de la fonction OH. Il a été démontré que cette anomalie du spectre était en rapport avec la présence d'eau dans le produit. Les essais mécaniques, par ailleurs, étaient en corrélation en accusant des valeurs de cisaillement en dessous des limites d'acceptation. La conjonction des deux contrôles a grandement facilité le règlement avec le fournisseur.

TABLEAU RECAPITULATIF DES PRINCIPAUX CONTROLES RECEPTION MATIERES Tableau n° 1

NATURE DES CONTROLES	PARAMETRES CONTROLES	METHODE UTILISEE	REFERENCES NORMES	CATEGORIES DE MATERIAUX				
				1 RESINES SOLVANTS	2 COLLES ADHESIFS	3 PREIM-PREGNES	4 TISSUS ET FIBRES SECS	5 CAOUT-CHOUCS
PHYSICO-CHIMIQUES	Conformité chimique	Spectographie I.R.		X	X	X		
	Taux solvants	Evaporation, pesée		X	X	X		
	Taux partie solide	"		X	X	X		X
	Taux cendre	Calcination, pesée		X	X	X		X
	Densité, masse surfacique, masse linéique	Pesée					X	X
	Caténaire	Mesure flèche des brins par rapport à 1 brin constituant tendu	AIR 9102				X	
	Taux d'imprégnation	Dissolution ou calcination - pesée				X		
	Viscosité	Viscosimètres BROOKFIELD ou HOPPLER		X	X			
	Pégosité (*)	Aucune méthode satisfaisante			X	X		
	Etat de fraicheur (*)	Aucune méthode encore définie		X	X	X		
	Aptitude à la vulcanisation	Rhéométrie						X
	Vieillissement accéléré	Chaleur humide de 70° C, 100 % H^2O/ 200 h, 500 h			X	X		
MECANIQUES	σ fibre (allongement %)	Traction sur mèche sens trame-chaîne	ASTM D 2343 ASTM D 638			X	X	X
	σ composite unidirectionnel	Pression hydraulique NOL Rings	ASTM D 2290			X	X	
	σ composite tissus	Flexion stratifiés	ASTM D 790			X		
	σ cisaillement composites	Flexion appuis rapprochés (NOL et stratifiés)	ASTM D 2344			X	X	
	Contraintes bidirectionnelles composite	Pression hydraulique capacité Ø 170 mm				X	X	
	σ cisaillement joints collés	Traction sur éprouvettes métalliques collées	AIR 4108 AIR 9108		X			
	Caractéristiques d'adhérence	Pelage (covulcanisation)			X			

(*) Ces types de contrôles sont actuellement l'objet d'études et de recherches

X = contrôles en cours d'exploitation

2.1.3 Etat de fraicheur et de pégosité des produits

Ces deux paramètres, d'ailleurs plus ou moins dépendants l'un de l'autre, posent des difficultés du point de vue de leur évaluation en contrôle qualité industriel.

- contrôle de l'état de fraicheur : il n'y a pas actuellement de mesures physico-chimiques directes de l'état de péremption. Dans une certaine mesure, la spectrographie infra-rouge permettrait de s'en faire une idée à condition de pratiquer l'analyse quantitative plus complexe de mise en oeuvre. Actuellement, on se borne donc plutôt à suivre les indications des fournisseurs relatives aux dates de péremption et aux conditions de stockage. Des essais mécaniques d'éprouvettes vieillies artificiellement contribuent, de plus, à accéder à une certaine assurance de la qualité en péremption des produits. Mais très fréquemment, ces essais donnent des résultats dispersés qui gênent les interprétations. Il est arrivé que des produits théoriquement bons, aient donné de mauvaises caractéristiques par cette méthode et inversement. Il n'y a rien d'étonnant à cela, lorsque l'on établit la liste des paramètres dispersifs, ne serait-ce qu'au niveau de la réalisation des éprouvettes. La nécessité de contrôles physico-chimiques directs de l'état de fraicheur est donc clairement établi.

- contrôle de la pégosité des préimprégnés et des films de colle :

  De l'état de pégosité dépend la qualité des stratifiés. Elle influe, en effet, sur l'aptitude à la mise en oeuvre donc sur la stabilité directionnelle du composite et sur l'évolution du "flot" de la matrice c'est-à-dire sur son taux et sur les porosités.
  Il n'y a jamais eu, en dépit de nombreuses tentatives éparses, tant en France qu'à l'Etranger, une philosophie nettement dégagée sur l'évaluation de l'état de pégosité. Actuellement, son appréciation reste essentiellement spécifique des cas d'utilisation et surtout, très suggestive, ce qui a parfois de fâcheuses conséquences en fabrication.

  Depuis plusieurs années, nous nous sommes intéressés à cette importante question et avons surtout cherché des solutions mécaniques au problème. Les conclusions de nos travaux nous amènent aujourd'hui à envisager l'introduction de moyens de mesures physico-chimiques en corrélation avec des tests mécaniques. Mais il serait souhaitable que le problème soit abordé sous un aspect plus général. En ce moment, d'ailleurs, le laboratoire central de la S.N.I.A.S. reprend ce problème en main. Il effectue actuellement une vaste campagne d'information pour faire le point avant d'entreprendre un programme de recherches associant différents utilisateurs de la Société.

  Dans l'immédiat et dans le cadre de nos applications industrielles, en attendant qu'une telle entreprise débouche sur des applications, il nous faut résoudre les problèmes latents qui risquent de perturber le rythme des productions. C'est pourquoi, avec les moyens existants au laboratoire et sur des objectifs à court terme, nous examinons quelques cas particuliers. Notre méthode consistera à rechercher des corrélations statistiques entre des classements d'états de pégosité appréciés par différents manipulateurs et les indications d'appareils de mesures physico-chimiques tels que le D.S.C., la chromatographie sur gel etc...

TABLEAU N° 2

TYPE D'APPAREILS D'ANALYSE PHYSICO-CHIMIQUE	APPLICATION PRINCIPALE	PRINCIPE	APTITUDE PROBABLE A L'EVALUATION INDUSTRIELLE DE LA PEGOSITE ET LA PEREMPTION
Chromatographie sur gel	Analyse macromoléculaire (gélification des résines)	Filtration du produit analysé à travers des tubes capillaires calibrés (mesure d'un temps d'écoulement)	Méthode de laboratoire intéressante mais assez complexe à mettre en oeuvre. Exige une grande vigilance d'entretien et d'étalonnage
Analyse thermique différentielle (D.S.C.) DUPONT	Mesure du point de transition vitreuse, évaluation des cycles de polymérisation	Microcalorimétrie basée sur les variations de capacité calorifique en fonction de l'état du matériau et de la température	Des travaux ont déjà été réalisés, dans cette voie, de bons résultats ont été obtenus
Gélographe (appellation provisoire) (Brevet S.N.I.A.S.)	Etude de cycles de polymérisation	Détection du début rigidité d'une éprouvette soumise à un couple de torsion en fonction de la température	Quelques observations encourageantes ont été faites dans le cas de préimprégnés polyimides
T.D.M.A. Thermo dynamic mechanical analyser (DUPONT)	Evaluation des caractéristiques mécaniques des composites en fonction de la température	Variation de rigidité d'une éprouvette soumise à de la flexion alternée Mesure des modules de rigidité	A voir
Iongraphing (Brevet Northrop)	Etude des cycles de polymérisations Conduite automatique des polymérisations	Evolution de la résistance électrique du matériau en fonction de ses variations d'état sous l'effet de la température	A voir
Audrey 300 Tetrahedron	Etude des cycles de polymérisations Conduite automatique des polymérisations	Evolution de la valeur du diélectrique du matériau en fonction de ses changements d'état sous l'effet de la température	A voir, d'après le Constructeur, la signature diélectrique du matériau peut être perturbée en fonction de son état de fraîcheur

2.2 Perspectives d'avenir

Il ressort donc de l'analyse ci-dessus, que l'effort doit être porté sur l'acquisition d'une meilleure maîtrise des paramètres physico-chimiques.

En préambule à la présentation de nos projets dans cette voie, nous ne manquerons pas de souligner l'importance que nous voyons à une rationalisation des actions dans ce genre de recherche. Il serait souhaitable de voir arbitrer cette coordination à l'échelon des services officiels spécialisés introduits dans de nombreux milieux industriels.

En ce qui concerne nos études futures, nous allons donc plus particulièrement, examiner la double question de la pégosité et l'état de péremption des produits dans le cadre de nos besoins industriels immédiats, et en liaison avec notre laboratoire central.

Le programme de travail comportera surtout l'évaluation de techniques de mesures physico-chimiques (voir le tableau n° 2) dont, certaines comme l'analyse thermique différentielle (D.S.C) ou la chromatographie sur gel sont déjà en application pour d'autres suivis industriels (définition de cycles de polymérisation pilotage de polymérisations, surveillance du degré de gélification des résines d'imprégnation...), mais également d'autres récemment apparues sur le marché français comme les mesures de diélectrique ou de résistance mécanique et électrique des matières plastiques comme le gélographe ou l'iongraphing. Des repères seront établis en fonction des appréciations des manipulateurs (pégosité), des corrélations seront établies avec des tests mécaniques.

3. CONTROLE NON DESTRUCTIF DES STRUCTURES

3.1 Politique adoptée pour le contrôle des propulseurs bobinés en fibre de verre

Le caractère particulier de la production de structures de hautes performances mécaniques de haut niveau de fiabilité, nous a conduits à un système de contrôle basé sur l'investigation unitaire et non destructive associée à des campagnes de dissection opérées sur des structures prélevées dans la série.

Il y a lieu de distinguer deux types de contrôle de ces structures :

- celui de la résistance mécanique de la coque à la pression interne de même que celle des liaisons collées des pièces rapportées,

- celui de la conformité fonctionnelle de certaines liaisons telles que celles des garnissages internes.

La nature du matériau composite à base de fibre de verre, sensible au vieillissement humide et la définition des structures présentant de nombreuses ouvertures dans un fond excluaient la pratique du timbrage garantissant habituellement les coques ayant à résister à la pression interne. En effet, dès la première mise en pression, la matrice époxy d'enrobage des fibres se craquèle et ne joue plus, au cours du stockage de l'engin, son rôle protecteur vis-à-vis des agents extérieurs. Il faut donc accéder à l'assurance de la qualité et de la fiabilité de ces structures par le biais d'une auscultation aussi poussée que possible pour qu'elle puisse à coup sûr révéler la présence des défauts. Dans cette optique, nous nous sommes limités à la détection des séparations interlaminaires considérées dans les structures stratifiées comme défauts majeurs.

Le processus consiste donc en une investigation globale et non destructive de l'ensemble de la coque résistante et de ses points d'attache, suivie d'une caractérisation fine des anomalies détectées (nature, importance et position) afin de pouvoir statuer sur les conséquences encourues pour la sécurité de la pièce et les réparations éventuelles.

3.2 Moyens mis en place

Le problème de la détection des défauts interlaminaires dans des matériaux isolants était nouveau puisqu'à l'époque, tout l'arsenal des moyens de contrôle était conçu pour les pièces métalliques et basé sur leurs propriétés physiques (conductivité, magnétisme). De plus, les défauts rencontrés dans les métaux (criques, soufflures) se présentent dans les trois dimensions par rapport au volume des pièces et sont donc plus aptes a être vus en radiographie.

Pour la détection de séparations interlaminaires dans des matériaux lamifiés isolants, la thermographie est certes le moyen le mieux adapté. Elle a le gros avantage de permettre l'auscultation globale des structures. Elle consiste à utiliser une caméra infra-rouge capable d'établir une carte de répartition des températures d'un objet avec une bonne précision et dans différentes gammes de températures. Pour nos applications, nous utilisons la gamme de température de l'ambiante à 100° C avec une précision de 1/4° C. Le procédé opératoire consiste à chauffer modérément (70° C) la paroi interne de la capacité par une circulation d'air chaud. On observe à l'aide de la caméra infra-rouge la paroi externe. Au droit d'une séparation interlaminaire, le flux de chaleur ne pouvant s'écouler, du fait de la discontinuité, le thermogramme traduira localement par une variation de densité optique l'écart de température résultant.

Mais les interprétations de la thermographie se compliquent singulièrement lorsque les parois présentent des évolutions d'épaisseur ou des pièces en insert. Ainsi, pour le contrôle des fonds avant de propulseurs qui présentent des variations d'épaisseurs et des inserts métalliques, il a fallu malgré le manque de souplesse de ces techniques pour nos applications, utiliser les ultrasons et la radiographie.

Les ultrasons sont également aptes à la détection des séparations interlaminaires puisqu'elles engendrent des réflexions parasites et même l'extinction totale du signal ultrasonore. Mais, dans les gammes de fréquences couramment utilisées pour les métaux, les matériaux composites sont très vite absorbants en fonction de l'épaisseur, ce qui limite les cas d'emploi.

Depuis quelques années, des appareils basse fréquence sont apparus sur le marché tel le "SONDICATOR". Ils sont mieux adaptés aux matériaux composites et donnent de bons résultats sur nos structures.

Pour la détection des séparations interlaminaires, la radiographie est mal adaptée, puisqu'elle est sensible aux variations de quantité de matière ou de densité qu'elle traduit en densité optique. Or, dans le cas de la séparation interlaminaire traversée perpendiculairement par le faisceau de rayons X aucune variation de matière n'intervient et le défaut passe inaperçu. La difficulté a cependant pu être tournée en présentant le défaut tangentiellement à l'axe du faisceau : c'est la "radiographie tangentielle" des coques de révolution bobinées. Cette technique a cependant le désavantage d'être longue et conduit à un nombre élevé de clichés à interpréter. Elle nécessite également des moyens de haute énergie compte tenu des épaisseurs importantes à traverser dans le sens tangentiel.

Dans la phase de caractérisation fine des anomalies résultant du sondage global des structures, les ultrasons et la radiographie sont les méthodes que nous considérons comme actuellement les plus efficaces. La thermographie qui permet de déceler la présence de défauts n'en donne pas un contour suffisamment précis, surtour, si la pièce est épaisse. Elle ne le situe également pas dans l'épaisseur. Nous avons donc coutume d'utiliser le SONDICATOR pour déterminer avec plus de précision les contours des défauts et la radiographie tangentielle pour les situer en profondeur.

Thermographie, ultrasons, radiographie basse et haute tension ont été regroupés dans une centrale fonctionnelle de contrôle non destructif dont la structure a été organisée en fonction de la gamme de contrôle afin de minimiser les transferts et les attentes entre chaque opération. Des moyens de mémorisation des informations sont également utilisés pour accroître les durées des interprétations sans grever les temps d'immobilisation des structures.

3.3 Examen des bilans d'exploitation de l'installation de contrôle non destructif

Des analyses statistiques de l'exploitation des contrôles de recette de deux types de propulseurs (I et II) que nous avons condensées dans les tableaux n° 3 et 4 ci-après, nous tirons les enseignements suivants :

- Tableau n° 3 :

CONTROLE NON DESTRUCTIF - CARTER TYPE 1	1ERE PERIODE JUIN 67 A MARS 72 (POUDRERIE)	2EME PERIODE AVRIL 72 A DECEMBRE 72 (S.N.I.A.S)
Nombre de structures contrôlées	77	33
Nombre de structures sans défauts	36	12
Nombre de structures avec défauts acceptées sans réparation	20	9
Nombre de structures avec défauts acceptées après réparation	18	9
Nombre de structures avec défauts rebutées	2	0
Nombre de types de défauts	12	10

- Tableau n° 4 :

CONTROLE NON DESTRUCTIF - CARTER TYPE 2	1ERE PERIODE JANV.72 A OCT. 73	2EME PERIODE OCT. 73 A JUIL. 74
Nombre de structures contrôlées	44	31
Nombre de structures sans défauts	33	28
Nombre de structures avec défauts acceptées sans réparation	8	1
Nombre de structures avec défauts acceptées après réparation	2	1
Nombre de structures avec défauts rebutées	1	1
Nombre de types de défauts	6	4

- en premier lieu, l'application des contrôles a permis d'éviter la livraison de structures comportant des défauts majeurs invisibles par simple inspection visuelle. Sur 77 structures du type 1, contrôlées dans la première période, 18 , présentant des défauts ont pu ainsi être réparées puis acceptées. Deux structures jugées non réparables ont été rebutées et déroutées de leur utilisation opérationnelle pour être affectées aux études pour analyses et expertises. Dans la seconde période, 9 structures ont été également réparées puis acceptées. Pour les structures du type 2, les mêmes constatations peuvent être établies.
- en second lieu, ces statistiques montrent que l'application du contrôle a contribué à des améliorations de la qualité de la fabrication. Nous constatons, en effet, que la quantité des défauts et leur variété diminuent d'une période à l'autre et d'une génération d'engins à l'autre.

3.4 Perspectives d'avenir du contrôle des structures bobinées

On peut donc considérer que le système actuellement en place répond aux exigences qui ont été définies pour les propulseurs actuellement en cours de production. Cependant, l'évolution normale de la technique, l'apparition des matériaux nouveaux comme le carbone ou le Kevlar, l'accroissement des dimensions des structures, nous obligent à reconsidérer la question.

L'accroissement des dimensions des structures a, en effet, des conséquences directes sur la radiographie qui nécessitera des moyens plus puissants. Il faudra passer des énergies de 400 KV à 10 MeV. Par ailleurs, la quantité de clichés à exploiter sera plus élevée, ce qui alourdira considérablement le système et les prix de revient.

Si l'utilisation de nouveaux matériaux maintenant moins sensibles aux facteurs de vieillissement (résines souples, fibre Kevlar) permet de reconsidérer la pratique du timbrage, ce dernier ne répond qu'à l'aspect fiabilité de la coque résistante du propulseur. Il faudra malgré tout assurer la qualité des joints fonctionnels et celle des liaisons des pièces rapportées. Il faudra faire appel de toute façon aux méthodes de contrôle non destructif. Ainsi, nous avons poursuivi nos recherches et prospections vers d'autres techniques telles que l'holographie et l'analyse acoustique avec comme objectif majeur de tenter de se passer au maximum de la radiographie dans la phase détection des défauts.

3.4.1 Point sur les recherches d'application de l'holographie au contrôle non destructif des capacités bobinées.

L'énorme développement constaté ces dernières années, dans le domaine de la technologie des lasers, notamment du point de vue de leur puissance, permet aujourd'hui d'envisager le contrôle industriel de pièces de révolution de grandes dimensions.

Il convient de mentionner ici, que l'industrie aéronautique emploi déjà l'holographie pour des contrôles de série, soit d'éléments panneaux sandwich, soit de pales d'hélicoptères. L'automobile a fait également appel à l'holographie dans le cadre des études pour résoudre des problèmes de vibration.

Le principe du contrôle holographique consiste à utiliser les propriétés de la lumière cohérente émise par les lasers qui permettent, par superposition de deux images correspondant à deux états de contraintes différents d'une pièce, de faire apparaître, sous forme de franges d'interférence, des microdéformations parasites liées à la présence de défauts.

L'avantage que nous voyons à l'holographie par rapport à la thermographie, par exemple, est qu'elle rend compte de déformations relatives aux défauts de la pièce sous charge. Elle peut donc rendre compte des répartitions de contraintes et faciliter ainsi, les décisions relatives à la fiabilité.

Les possibilités expérimentales de l'holographie sont assez nombreuses :

- il y a d'abord plusieurs types de sollicitations possibles (thermiques, mécaniques, statiques ou dynamiques).

- il y a également plusieurs méthodes d'observation :

  . en temps réel,

  . en double exposition ou "franges gelées",

  . en temps moyenné.

Enfin, il existe deux familles de lasers, ceux dont l'émission est continue (à la longueur de cohérence près) et, ceux dont l'émission est impulsive mais d'un niveau énergétique considérable par rapport aux précédents et qui permettent l'holographie en milieu perturbé.

La sensibilité de la méthode holographique est telle, qu'avec les premiers lasers de faible puissance (quelques mW), il fallait expérimenter dans des conditions d'isolement sévères vis-à-vis des vibrations car les temps d'exposition étaient très longs.

Les premiers travaux réalisés sur capacités maquettes se sont très vite révélés encourageants : la plupart des défauts détectés par les autres méthodes l'étaient également par holographie. Actuellement, ces travaux se poursuivent sur des structures à grande échelle et nous expérimentons dans les deux voies des lasers continus de forte puissance (4 à 10 W) et des lasers à déclencher. Les premiers hologrammes obtenus dans l'un et l'autre cas sont de qualité équivalente.

Actuellement, nous sommes en droit de penser que l'holographie associée à la thermographie devrait permettre de se passer de la radiographie en tant que moyen de détection de défauts. Ceci constituerait pour le contrôle des liaisons fonctionnelles, un allègement sensible.

3.4.2 Point de nos travaux sur l'analyse acoustique.

Les émissions d'ondes de contrainte émanant d'une pièce sous charge sont caractéristiques de la structure du matériau la constituant.

Les progrès rapides réalisés en électronique permettent de collecter ces signaux dans des bandes de fréquence très élevées, de les trier, les mémoriser, les compter et de les caractériser en énergie, amplitude et fréquence.

En métallurgie, l'analyse acoustique connaît déjà des applications, notamment pour la surveillance de pièces de sécurité en fonctionnement. On sait actuellement, détecter et localiser des fissures dans des métaux et suivre leur évolution en cours d'utilisation.

Dans le domaine des structures en matériaux composites, les recherches sont bien engagées certaines observations et interprétations sont en concordance entre plusieurs laboratoires spécialisés dans les matériaux composites.

Ainsi, nos travaux relatifs à l'évaluation par émission acoustique de l'endommagement par vieillissement de capacités bobinées rejoignent certaines observations du laboratoire des Mines de Paris. Notamment, au sujet de l'effet KAISER sur les composites endommagés.

Les relations que nous venons d'engager avec le laboratoire de Lawrence Livermore ont été également fructueuses et nous encouragent à poursuivre nos recherches dans l'application de l'analyse acoustique pour l'évaluation prévisionnelle des performances des capacités bobinées. Il a notamment été établi, à partir d'un nombre important de capacités timbrées, une corrélation entre la quantité d'émissions et le niveau de performance à rupture. Plus une structure est émissive, moins sa performance est élevée.

On voit ainsi qu'un meilleur parti pourrait être tiré des épreuves de timbrage en accédant à l'évaluation prévisionnelle de la fiabilité des structures.

Mais pour établir des critères d'acceptation suffisamment fiables, des études fondamentales associées à de nombreuses expérimentations sur maquettes et structures réelles sont encore nécessaires.

3.4.3 Exemple de projet de plan de contrôle adapté à des structures de grandes dimensions.

Dans les phases de développement et de présérie, il est évident qu'un maximum d'informations doit être collecté et, de ce fait, toutes les méthodes devront être utilisées en parallèle.

Ainsi, on confronterait l'épreuve de timbrage, associée à l'analyse acoustique, l'holographie et la mesure de déplacements de points repères de la capacité avec l'investigation classique à l'aide des moyens non destructifs, ce qui permettrait d'ajuster dans son détail, le plan de contrôle destiné à la série.

En ce qui concerne le contrôle des structures de série, on peut en tracer les grandes lignes (voir l'organigramme n° 5 ci-contre) :

a) la garantie en recette de la coque résistante pourrait être acquise par l'épreuve de timbrage associée à :

- l'analyse acoustique,
- l'holographie,
- la mesure de déplacements de points repères .

Des examens C.N.D. partiels ou complets pourraient être décidés en fonction des résultats obtenus.

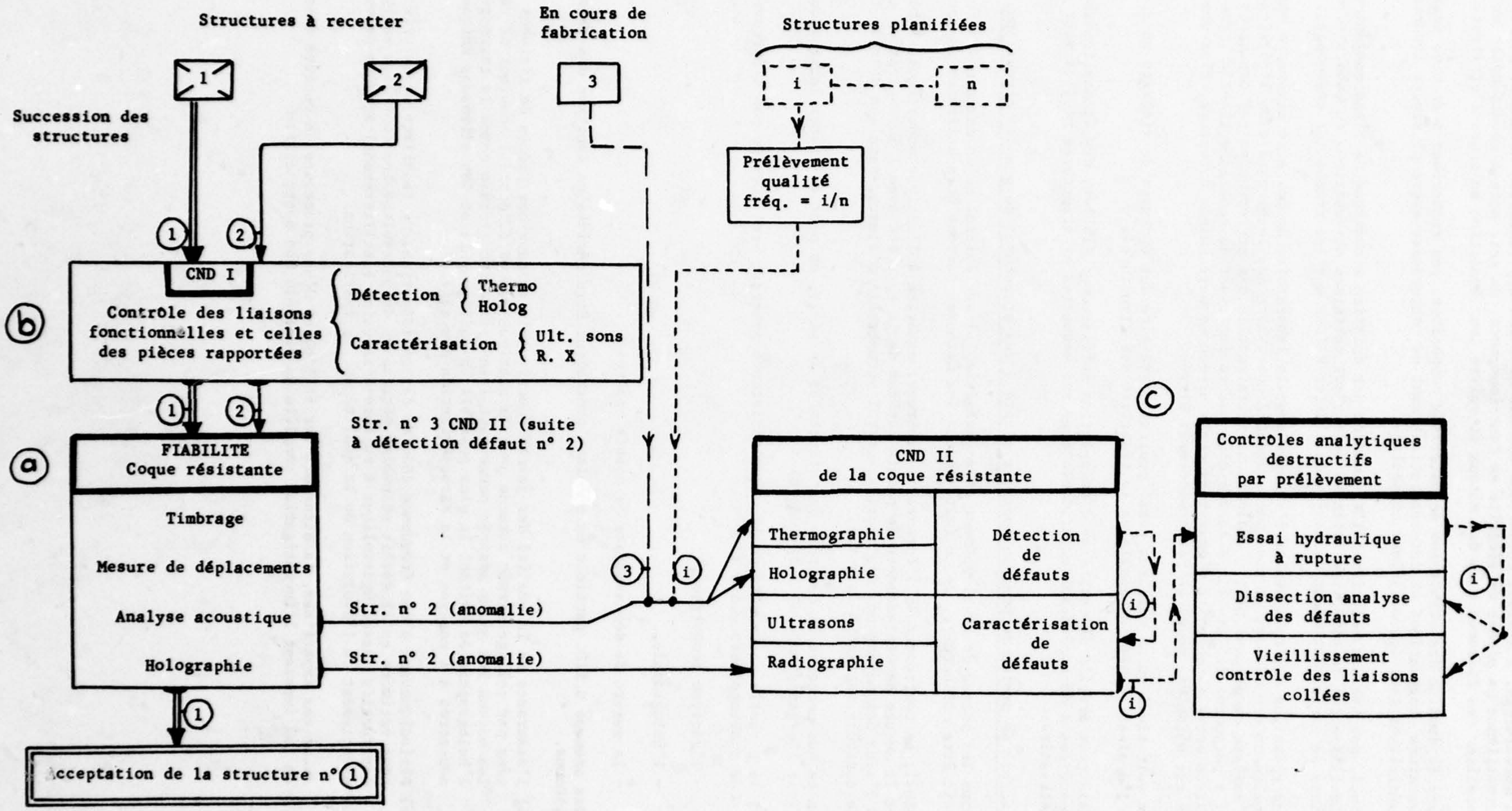
b) l'assurance de la qualité des joints fonctionnels et ceux des pièces de liaisons rapportées par collage serait obtenue pour la pratique du C.N.D. dont il convient de rechercher les moyens les mieux adaptés permettant l'investigation globale comme la thermographie ou l'holographie en évitant le plus possible la radiographie et les ultrasons uniquement consacrés à l'analyse et la caractérisation des défauts.

c) Périodiquement à une fréquence déduite de considérations de fiabilité et de prix de revient nous estimons qu'il serait néanmoins nécessaire de poursuivre les contrôles analytiques destructifs (essai hydraulique à rupture dissection vieillissement) afin de pouvoir juger directement de l'évolution de la qualité de la fabrication.

Avant ces expertises, la structure ferait l'objet d'une procédure de recette élargie en lui imposant l'investigation complète du contrôle non destructif.

TABLEAU N° 5

PLAN DU CONTROLE QUALITE DES STRUCTURES NOUVELLE GENERATION



4. CONCLUSION

Depuis une douzaine d'années, un long parcours a été réalisé dans le domaine des contrôles industriels des matériaux composites et des structures en découlant. Dans le cadre très exigeant des engins spaciaux, le système actuellement mis en place à la S.N.I.A.S. donne satisfaction pour les structures en cours de fabrication. Notons, à ce sujet que, jusqu'à présent, aucun incident de vol n'a pu être imputé à une défaillance de nos structures.

L'évolution de la technique, l'utilisation de nouveau matériaux, les définitions plus audacieuses des engins nous obligent à poursuivre nos recherches sur l'assurance de la qualité et de la fiabilité en veillant cependant à l'allègement des opérations de contrôle en introduisant des moyens mieux adaptés et par la gestion statistique de la qualité.

DETECTION OF FLAWS IN METALLIC AND NON-METALLIC COMPOSITE STRUCTURES USING LIQUID CRYSTAL TECHNOLOGY

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This paper discusses the nature of liquid crystals and their application to non-destructive testing of composite structures. Experimental techniques using brush-on liquid crystals and custom liquid crystal films is illustrated and discussed. The types of metallic and non-metallic composites that have been successfully tested using this technique are: (1) Aluminum skins and aluminum honeycomb core, (2) Aluminum skins and high temperature phenolic core, (3) Aluminum skins with Mylar core, (4) Glass cloth skins with glass fiber honeycomb core, (5) Titanium skins with aluminum honeycomb core, (6) Titanium skins with high temperature phenolic core, and (7) Glass cloth laminates. This technique accurately and reliability defines the size and shape of material defects. Non-destructive tests based upon liquid crystal technology have been demonstrated with hardware such as missile wings and elevons, aircraft and helicopter blades, composite body structures, and numerous types of electronic equipment. This new non-destructive testing technique is relatively inexpensive, easy to utilize and interpret, and completely reliable. L. C. technology will play a significant role in future cost-savings and reliability of flight hardware.

Using the unusual optical properties of cholesteric liquid crystals, the US Army Missile Research and Development Command, Redstone Arsenal, AL, has developed a new method for non-destructive testing of composite materials. This technique can also be used for non-destructive investigation of laminated structures, printed circuit boards, and other electronic components. Although the potential of liquid crystals for non-destructive testing applications has long been recognized, difficulties in handling them have limited their use. These problems have been overcome by encapsulating the crystals and impregnating them onto cheap, reuseable films. In comparison to other NDT methods, this technique is simple, reliable, and offers the potential of significant savings in time and cost.

This paper describes research and development efforts related to the new technique. More specifically, it describes the development of liquid crystals; discusses MIRADCOM's adaptation of the unusual thermosensitive optical properties of cholesteric liquid crystals to non-destructive testing; describes the development of manufacturing techniques necessary to encapsulate and impregnate those compounds onto cheap reuseable films; and discusses potential applications of this technology.

BACKGROUND

Frederick Reinitzer, an Austrian botanist, discovered the intriguing and confusing phenomen known as the liquid crystalline state in 1888. Reinitzer heated cholesteryl benzoate and observed what appeared to be two melting points. At 145 C the solid structure collapsed to form a turbid liquid, which, on further heating, became transparent at 179 C. This imtermediate mesomorphic phase became known as the liquid crystalline state.

Liquid crystals are compounds that go through a transition phase that is intermediate between a solid and a liquid. A crystalline solid possesses definite volume and shape. Its molecules are arranged in definite geometrical configurations. The liquid state, on the other hand, is characterized by molecular mobility in three directions and a total lack of molecular orientation. Between these two clearly defined states, there are some crystalline organic substances that, over clearly defined temperature ranges, appear to possess the flow characteristics of a liquid while retaining much of the molecular orientation of the crystalline solid. This is the liquid-crystal state first observed by Reinitzer. The relationship between these three states is illustrated in Figure 1. These phase changes are, of course, reversible. As the true liquid cools, it passes once again through the liquid-crystal state before crystallizing into a true solid.

Liquid crystals are not as extraordinary as one might suppose. It is estimated that approximately one in every 200 organic compounds passes through this phase. The unique physical and chemical properties of liquid crystals, together with their wide occurrence in both inanimate and animate matter, make them valuable to chemists, biologists, physicists, and medical scientists.

There are commonly three designations of liquid crystals: smectic, nematic and cholestric, these are illustrated in Figure 2. In the smectic configuration, molecules are oriented parallel to each other in well-defined planes, somewhat like successive layers of honeycomb. In the nematic configuration, the molecules are also parallel, but they do not exhibit planar cohesion. The cholesteric state is similar to the nematic, but the molecules are helically displaced to a slight degree. A stack of library cards, each with one corner bent-up has been used as a modle to illustrate the displacement or overall configuration of this state. Since the derivatives of cholesteral, principally the esters, are important representatives of this configuration, the name "Cholesteric" has been given to the entire class. Pure cholesteral, shown in Figure 3, is the steroid that is blamed with so many of our circulatory illnesses today, but does not itself act as a liquid crystal. Only its derivitives possess the unique optical properties applicable to the field of non-destructive testing.

Cholesteric esters, as represented in Figure 4, exhibit the behavior which lends their name to this entire class of liquid crystals. It is this cholesteric crystalline state which possesses the unique optical properties that we are now finding applicable in the field of non-destructive bond inspection.

Figure 5 illustrates some of the optical consequences of the molecular order of cholesteric crystals.

1. BIREFRINGENCE - Birefringent materials transmit light waves at different velocities in different directions through the material. All liquid crystals including the nematic and smectic states, have this facility.

2. OPTICAL ROTATION - Optical rotation of polarized light occurs only in the cholesteric state. Cholesteric crystals are, in this respect, the most optically active substances known, since they rotate light through an angle several hundred times that of the usual optically active materials.

3. SCATTERING OF WHITE LIGHT - White light is scattered to reflect different wavelengths, giving iridescent colors. Colors observed are a function of the specific cholesteric substance, the angle of reflected and incident radiation, and the temperature. This property allows the utilization of cholesteric crystals in visual inspection techniques. These materials are generally colorless on each side of the liquid-crystal state -- colorless, that is, in the true solid and the ultimate true liquid phase. Each cholesteric liquid crystal responds in its own way to changes in temperature. The change may be only from red to green, or from red through the entire color spectrum, or from green to blue. The important characteristic is that each color corresponds to an exact temperature of the material being tested.

The unique properties of liquid crystals that make them valuable non-destructive testing tools are their sensitivity to thermal changes and their ability to respond to chemical impurities. Since liquid crystals reflect colors determined by the temperature of their environment, they may be used to project a visual, color picture of the transient temperature anomalies, or minute thermal gradients, associated with material discontinuities. These discontinuities, which may be failed bonds, cracks, or other defect areas impede the flow of heat sufficiently to disturb the normal temperature patterns of a material being tested. The defects will show up as distinct color patterns, because of their impaired thermal transmission characteristics. This is illustrated in Figure 6. In like manner, color response to chemical environment may be used for detection of flaws by interaction of the liquid crystals with chemical impurities concentrated in the defect area.

As stated previously, the iridescent colors of liquid crystals arise from light reflectance. For most effective observation it is necessary to have a dark background, normally prepared by using a water-soluble black paint.

We began our development of liquid crystal systems for debond detection with evaluation of the commercial materials available to us. These cholesteric compounds and mixtures of compounds exhibit color sensitivities over ranges as small as one degree centigrade, or as large as 30 degrees. A sensitivity range of one degree is sufficient to define defects in composite materials with aluminum skin thicknesses of 20 MILS or less. Our specific requirements, however, are for nondestructive inspection of composite structures with aluminum skins as thick as 60 MILS. For this purpose, liquid crystal mixtures with sensitivity ranges of much less than one degree are required. Our approach was to blend available cholesteric esters to achieve increased temperature sensitivities.

Figure 7 illustrates the light reflectance of individual cholesteric esters as a function of their structure. The ranges of colors observed during a heating or cooling cycle are plotted against the number of carbon atoms in the acid group of cholesteric esters. Starting with the first position on the graph, neither the formic nor the acetic esters showed any color when heated through the liquid crystal state, whereas the propionic ester goes through the entire color spectrum. Evaluation of esters through the 18 carbon acid revealed no pattern to the color changes.

Figure 8 shows the observed color change range as a function of cholesteric ester structure. The color change amplitude of the ester of the three carbon acid is 35 degrees, and that for the 18 carbon acid is approximately three degrees. Obviously, blended mixtures are required to achieve the sensitivities desired.

Figure 9 shows the color behavior of blends of cholesteric pelargonate with cholesteryl butyrate. The compositions of the individual blends are plotted against the color change range. Pure cholesteryl pelargonate, on the left, has a color change diversity of 15 degrees. When 5 percent cholesteryl butyrate is added, the range becomes one degree centigrade. Likewise, cholesteryl butyrate, on the right, shows a decreased range when blended with 5 percent cholesteryl pelargonate. From this chart, it is evident that one material blended with a relatively small amount of a second material produces the most pronounced decrease in color change range. Using the same approach on other materials, we have developed blends which go through the entire spectrum of colors in 0.1 centigrade or less.

A blend was applied to composite panels with three types of debond simulations. In the first instance a teflon insert was incorporated between the skin and the adhesive. This is a fair simulation of such common bonding errors as oil on the inner surface of the skin. Of synthetic debonds that we have tried, we have found the teflon insert to be the most difficult to detect. For this reason, all promising systems were first evaluated on panels with teflon inserts. The second simulation was crushed core which gives the most sharply defined outline of the defect. The last simulation checked the effect of precured adhesive. This gave an equally well-defined defect outline.

The best blends work equally well on composite structures with skin thicknesses of 20 MILS (Figure 10), 60 MILS (Figure 11), or 190 MILS (Figure 12). The minimum defect definable in structures with skin thicknesses of 60 MILS is one crushed honeycomb cell (a 1/16 inch hexagon), and in composites with 190 MIL skins, the minimum detectable defect is 1 square inch.

The following composite structures have been investigated with equal success:

(1) Aluminum skins with high temperature phenolic (HRP) honeycomb core.
(2) Glass cloth skins with glass fiber honeycomb core.
(3) Titanium skins with aluminum honeycomb core.
(4) Titanium skins with HRP honeycomb core.
(5) Glass cloth laminates

In the course of this work, we have found that incandescent lighting is best suited for these observations, although fluorescent lighting is adequate. We have also found that temperature control is best achieved with simultaneous heating and cooling. For example, a test panel is heated on one side and cooled on the other. Figures 13, 14, and 15 show the color sequences observed during the heating of one crystal system through its liquid crystal state. Notice that the defect pattern remains unaltered except for color changes.

Figure 16 shows testing of a missile wing, which is a composite structure of aluminum honeycomb sandwiched between 60 MIL aluminum skins. The defective area is clearly observable as an isolated color pattern. It was felt that thermal conversion of mechanical energy during deformation could be detected and visualized with the aid of liquid crystals in a manner leading to increased understanding of flow and fracture processes.

Figure 17 shows an aluminum dogbone sample being pulled on an instron tester. The center color indicates a warmer area - or the area of concentrated stress. Studies of this type might help in analysis of phenomena such as nonhomogeneous plastic flow: Location of slip and slip saturation during fatigue; and fatigue crack initiation and growth characteristics. In this test, plastic flow of samples was marked by local temperature increases before necking of the specimen bacame visible.

Figure 18 shows an aluminum rod being subjected to stress on a rotary beam fatigue tester. The necked-down center area is purple. This indicates the warmest temperature for this section of the rod. The ends of the rod are cooler, as indicated by colors corresponding to lower temperatures.

Figure 19 shows a series of 4 resistors. The black one did not heat up when current was applied and therefore is defective. "HOT SPOTS" caused by poor connections can be pinpointed by isolated color patterns. Crystals with a permanent color change, called memory crystals, might prove to be more practical for hot spot detection.

Figures 20 and 21 show the fuel support panel of a helicopter being investigated. This helicopter has been used to launch missiles in battlefield conditions. The reddish-brown areas are the unbonded areas that resulted from shock waves.

In order to simplify the use of liquid crystals for NDT, MIRADCOM developed a process for encapsulating the crystals and impregnating them onto reuseable films. These films are manufactured in rolls that are 1500 feet long and 3 feet wide. They are prepared by encapsulating the liquid crystals in a polyurethane matrix, and laminating them between polyester films -- one of which is transparent and the other has a black coating on the back of it. The resultant laminate provides an even, intense color display between 71.5 C and 72.1 C.

We have found the vacuum bag technique (illustrated in Figure 22) to be the most efficient way to use these films. This process allows the films to conform to almost any irregular shape and of course, they are reuseable. We plan to explore the possibility of using the film itself as the vacuum bag. This technology has been applied to upgrading weapon systems component reliability. Non-destructive tests based upon liquid crystal technology have been demonstrated with hardware such as missile wings and elevons, aircraft and helicopter blades, helicopter composite body structures, and numerous types of electronic equipment. Other applications include checking of special insulation required to prevent contact of dissimilar materials and bonding of solid propellant to metal or fiberglass cases.

In summary the establishment of a manufacturing technique for producing these new films will permit the development of a new non-destructive testing technology that will play a significant role in the future reliability of defense hardware. We believe that the liquid crystal systems are the simplest most reliable, and most economic method for evaluating bond defects in matallic and nonmetallic composite structures.

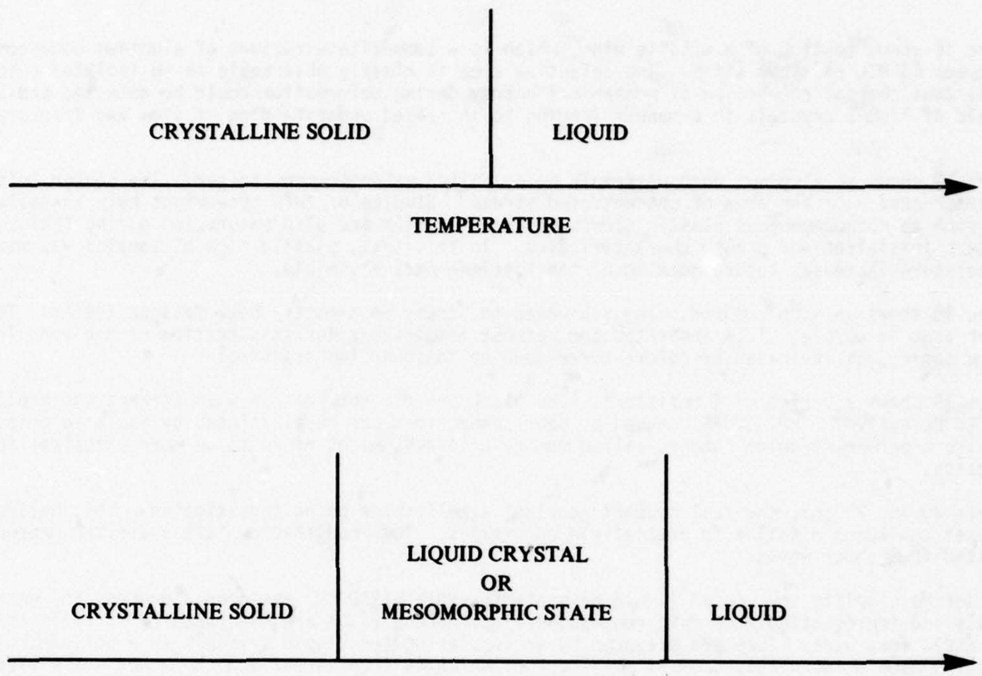

Fig. 1 Temperature dependence of liquid crystal state

A. SMECTIC-PARALLEL ORIENTATION OF MOLECULES IN WELL DEFINED PLANES

B. NEMATIC-PARALLEL ORIENTATION OF MOLECULES BUT WITHOUT PLANAR COHESION

C. CHOLESTERIC-PARALLEL ORIENTATION WITH HELICAL DISPLACEMENT

Fig. 2 Classes of liquid crystals

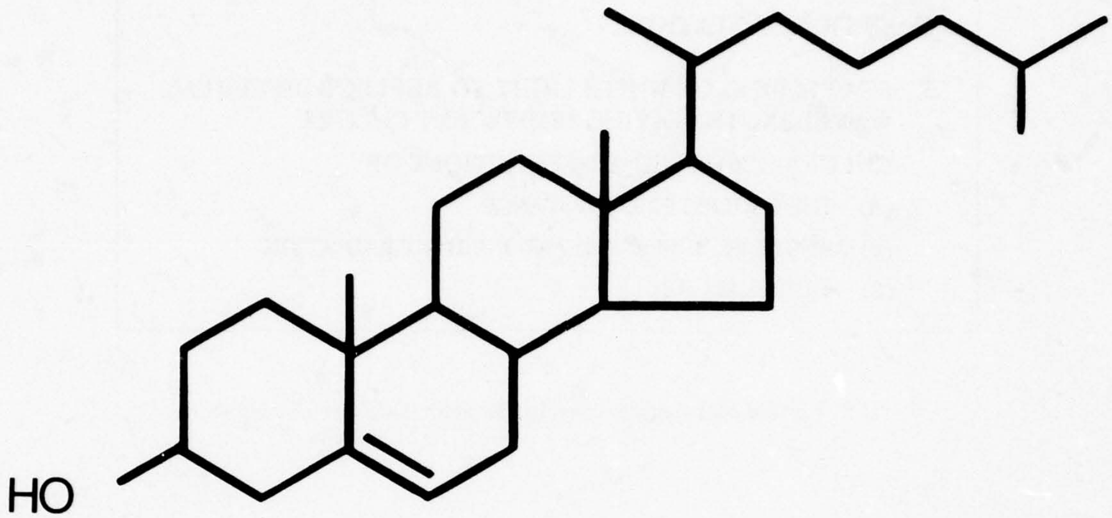

Fig.3 Cholesterol

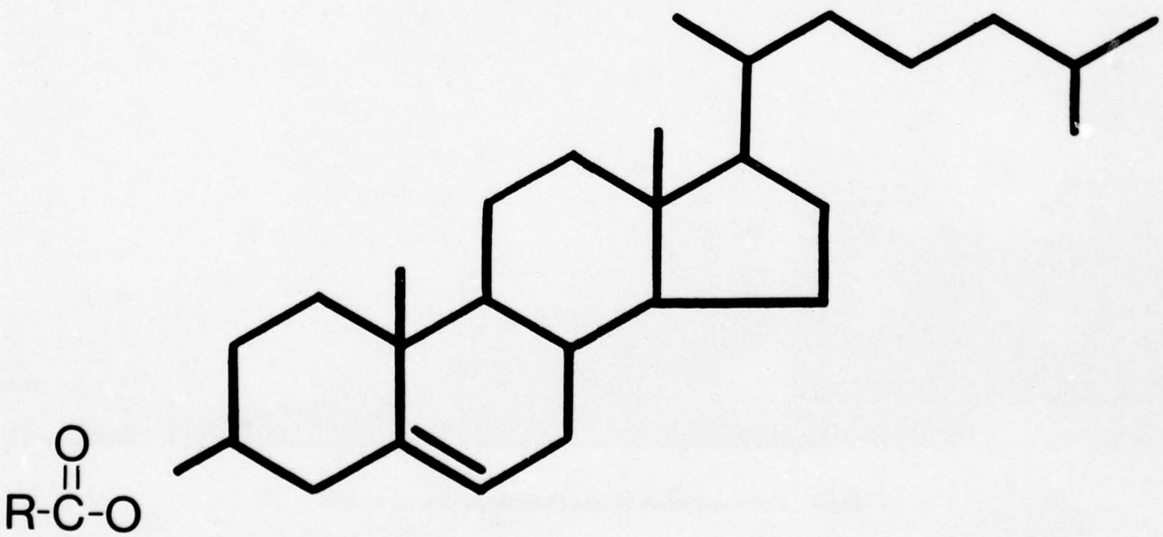

Fig.4 Ester of cholesterol

1. BIREFRINGENCE
2. OPTICAL ROTATION
3. SCATTERING OF WHITE LIGHT TO REFLECT DIFFERENT WAVELENGTHS GIVING IRIDESCENT COLORS

   COLORS OBSERVED ARE FUNCTIONS OF:

   (A) THE CHOLESTERIC SUBSTANCE

   (B) ANGLE OF REFLECTED AND INCIDENT RADIATION

   (C) TEMPERATURE

Fig.5 Optical consequences of molecular order in cholesteric crystals

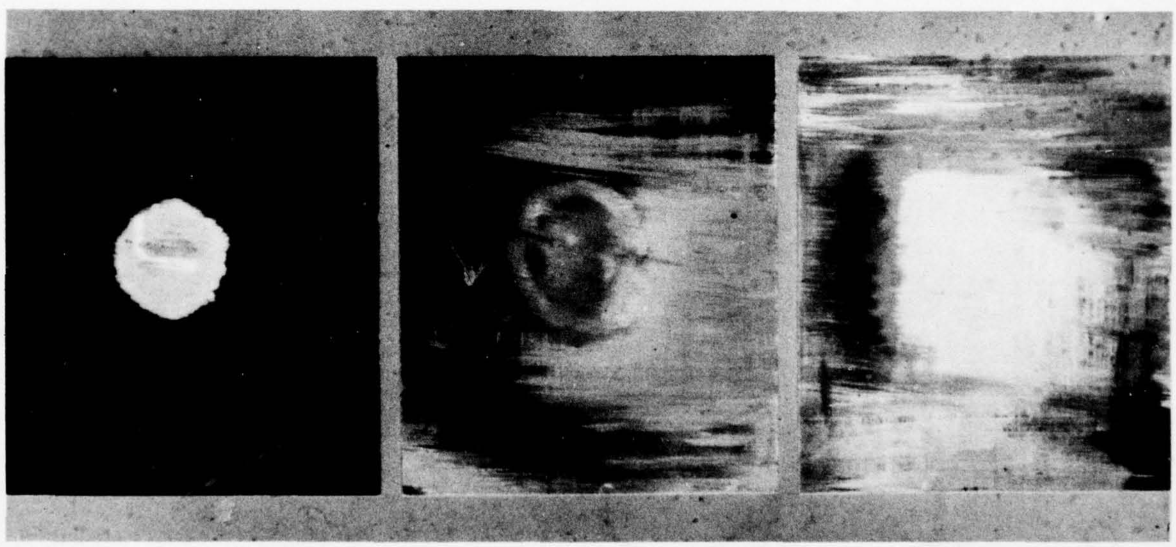

Fig.6 Color sequence of one cholesteric crystal system

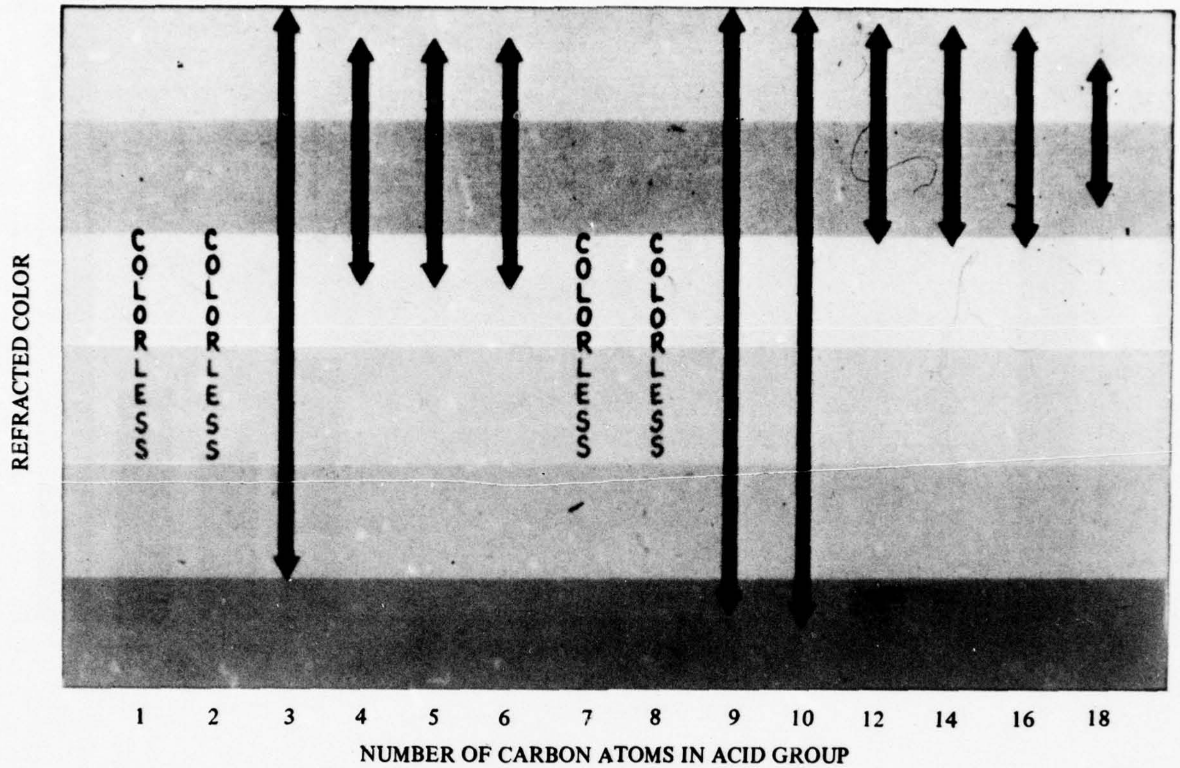

Fig.7 Observed light reflectance as a function of cholesteric ester structure

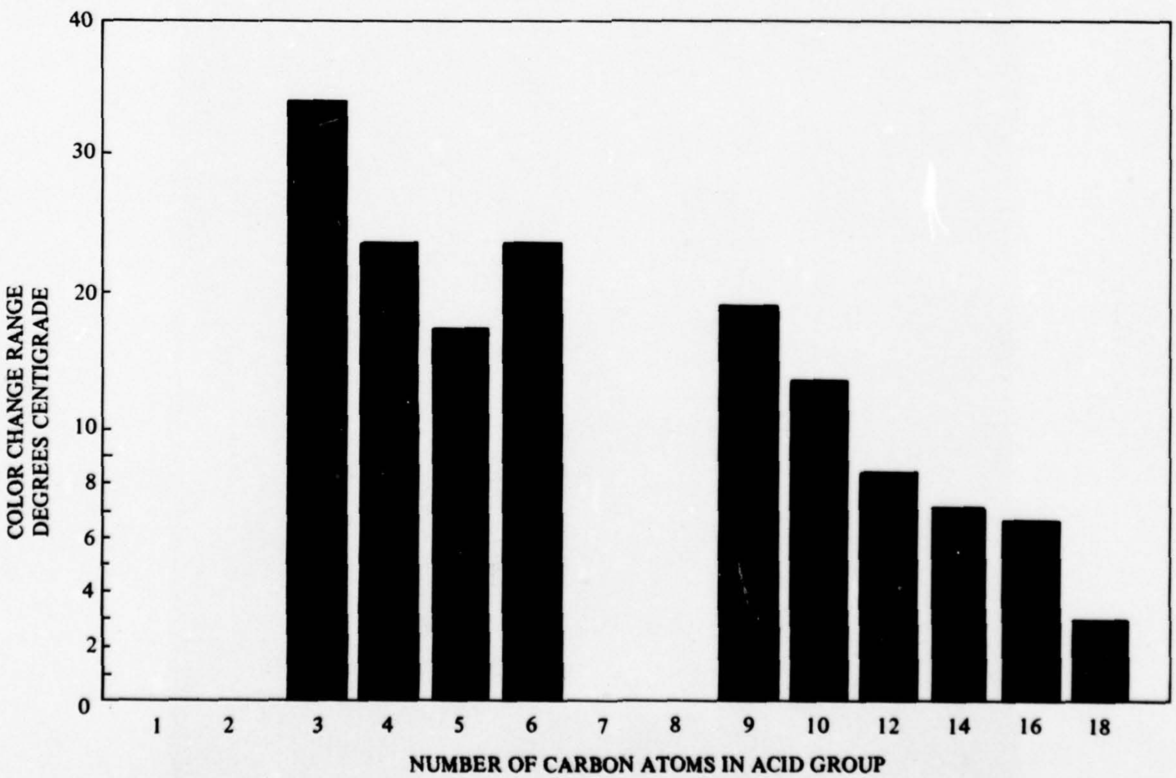

Fig.8 Observed color change range as a function of cholesteric ester structure

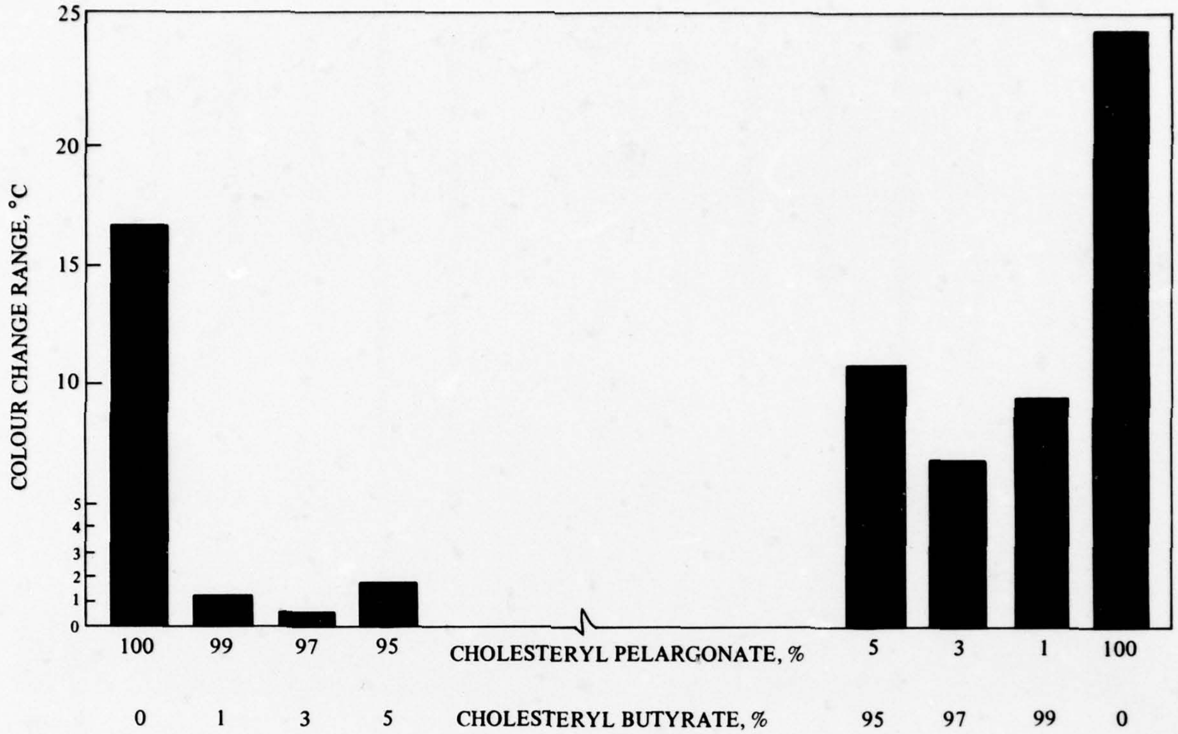

Fig.9 Color change range of blended systems

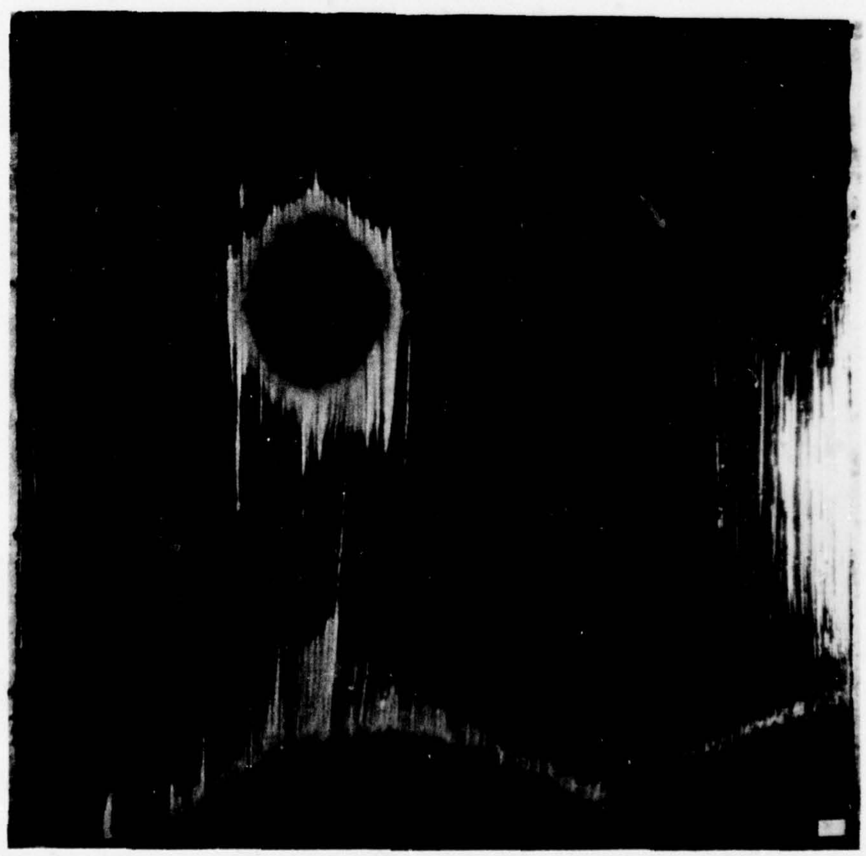

Figure 10

Figure 11

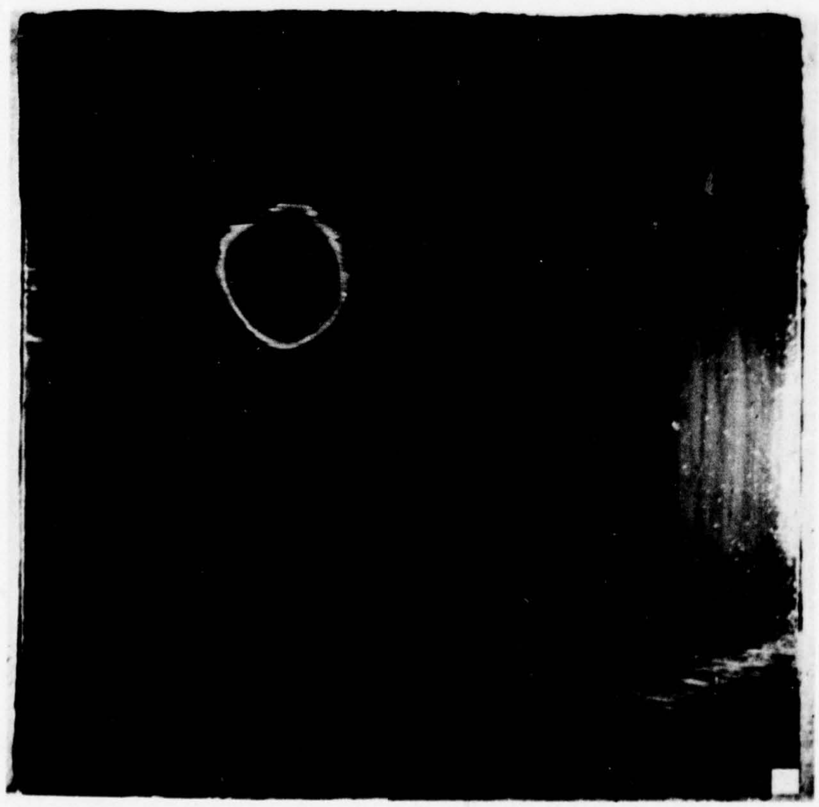

Figure 12

Figure 13

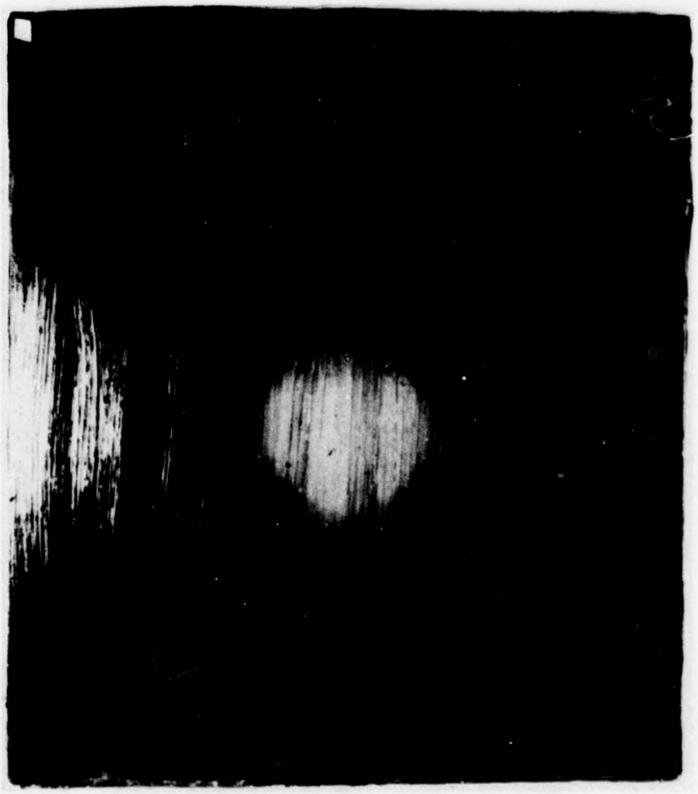

Figure 14

Figure 15

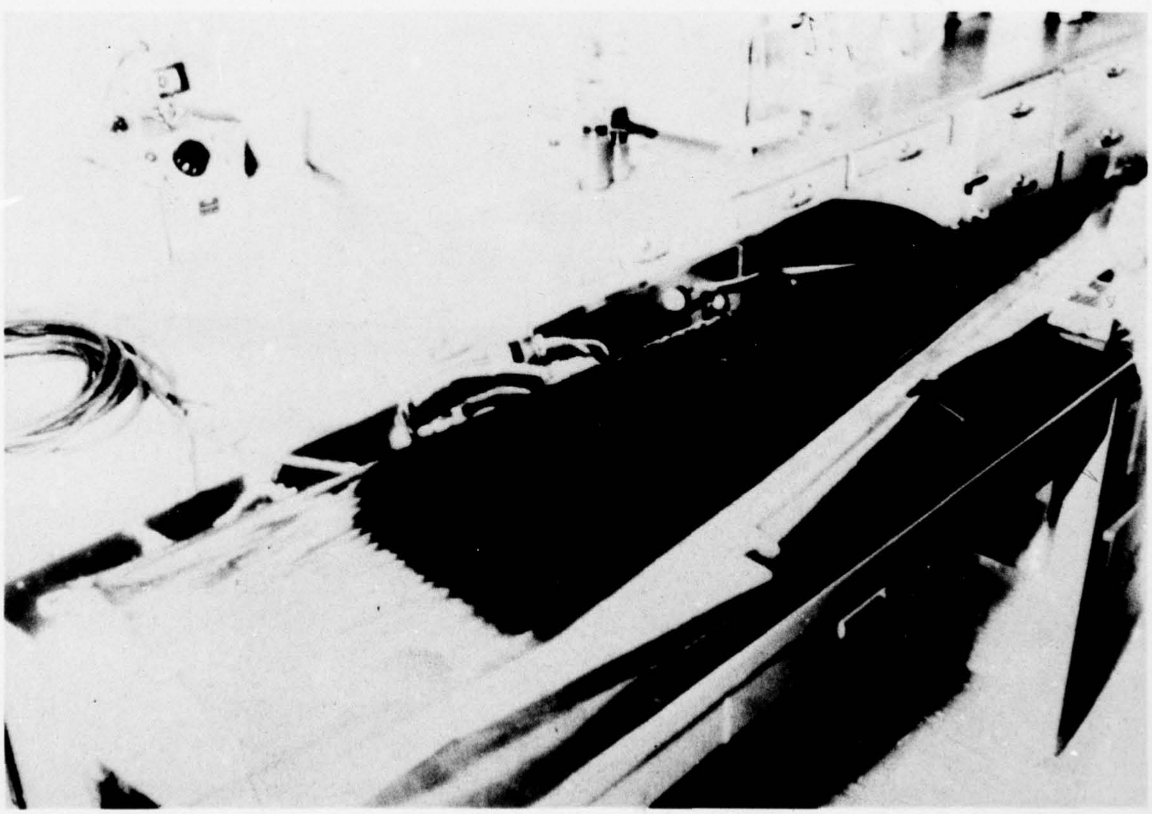

Figure 16

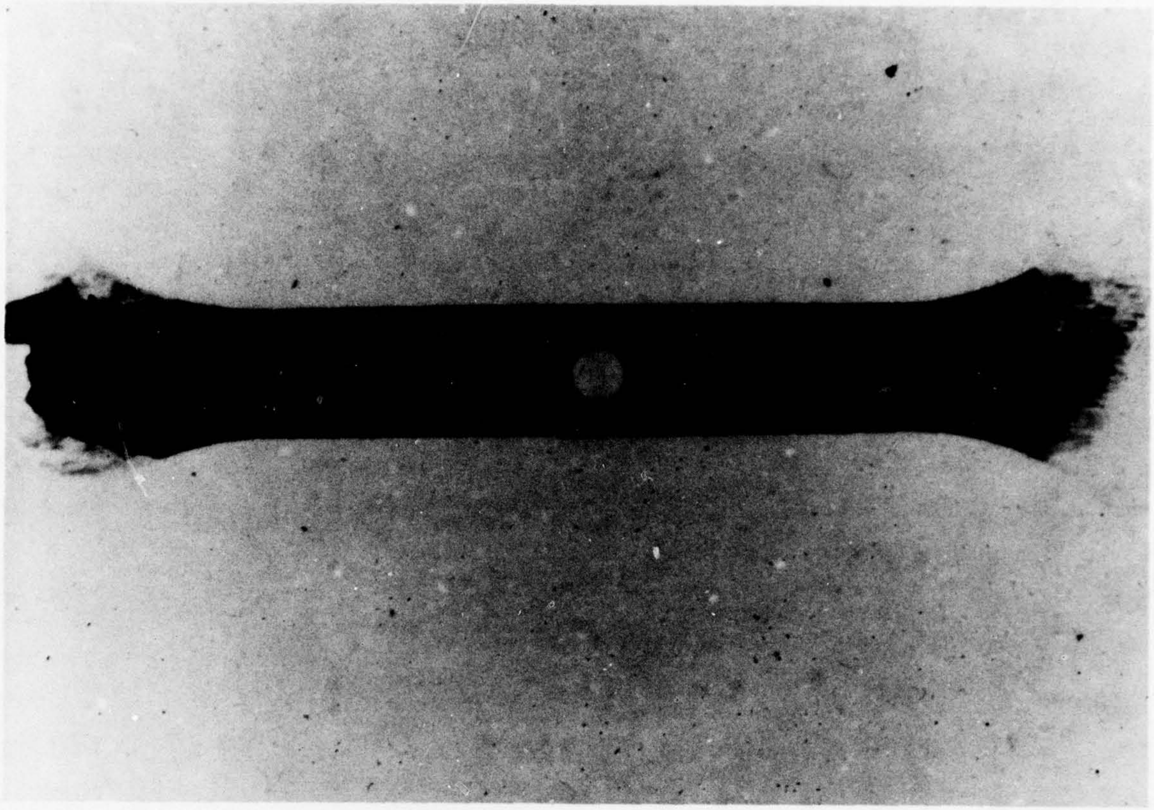

Figure 17

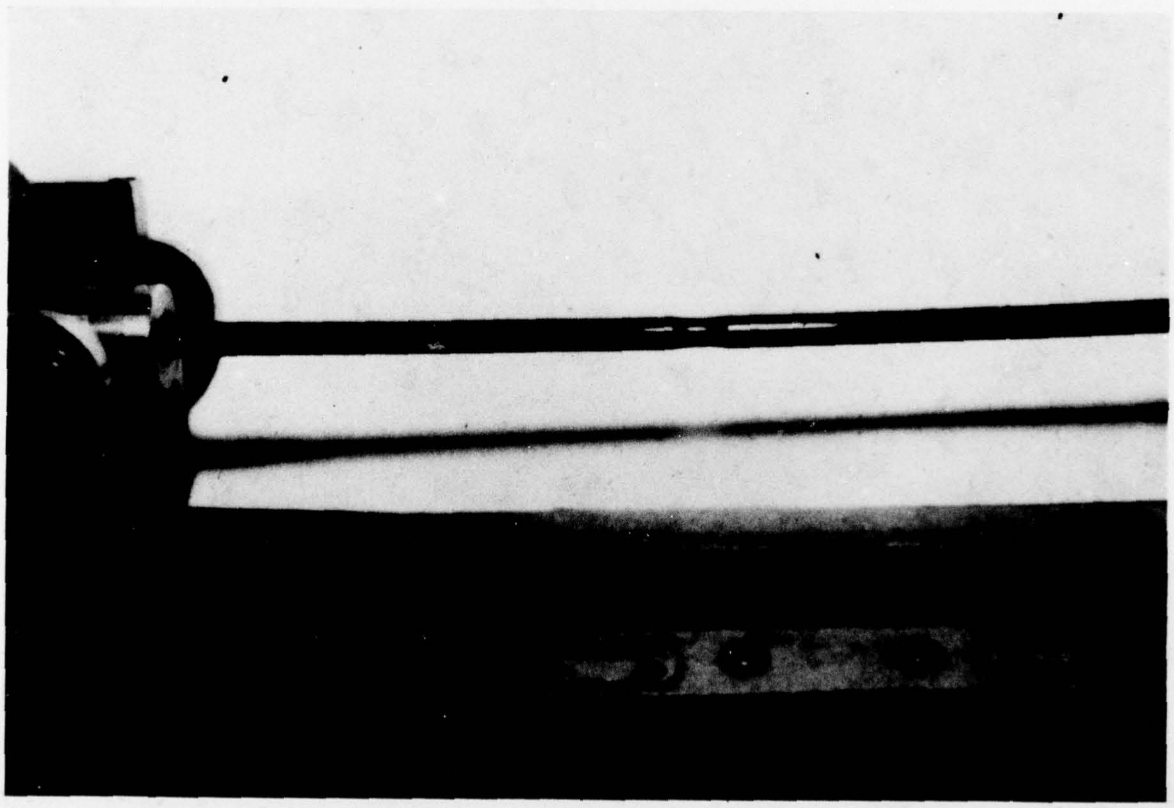

Figure 18

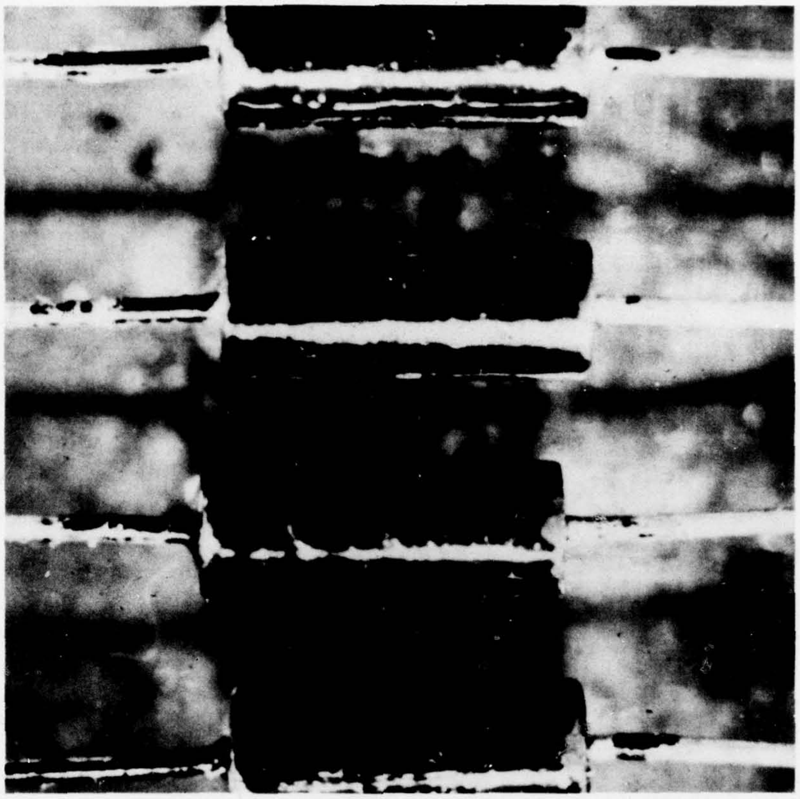

Figure 19

Figure 20

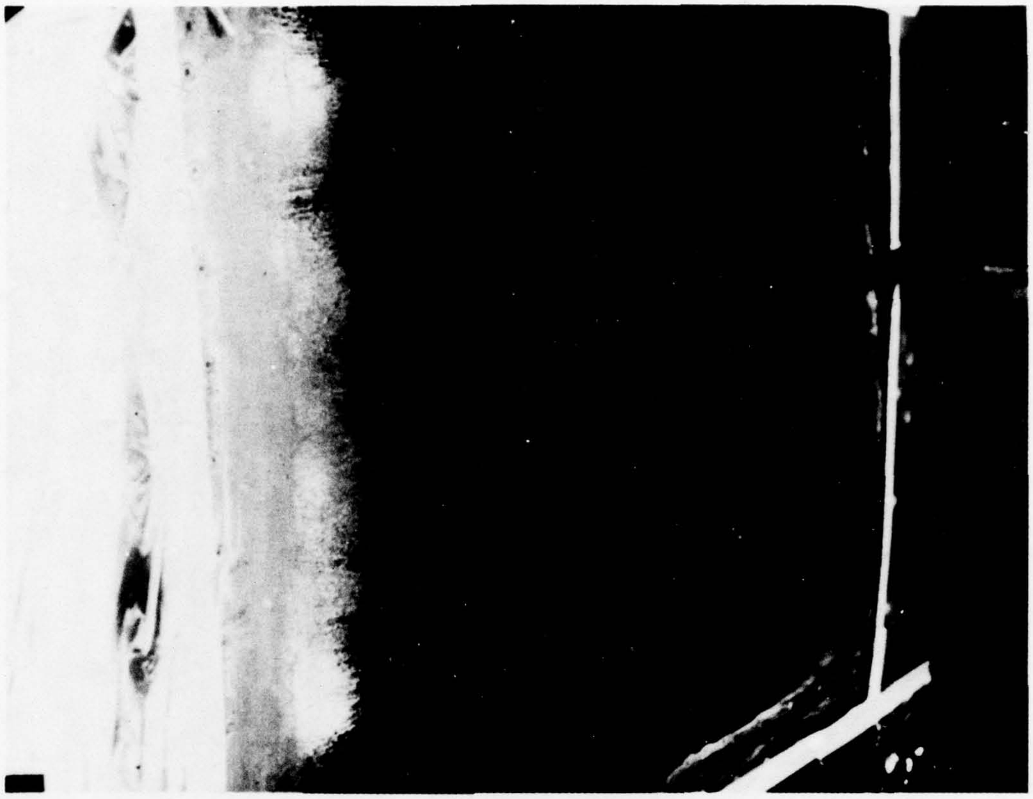

Figure 21

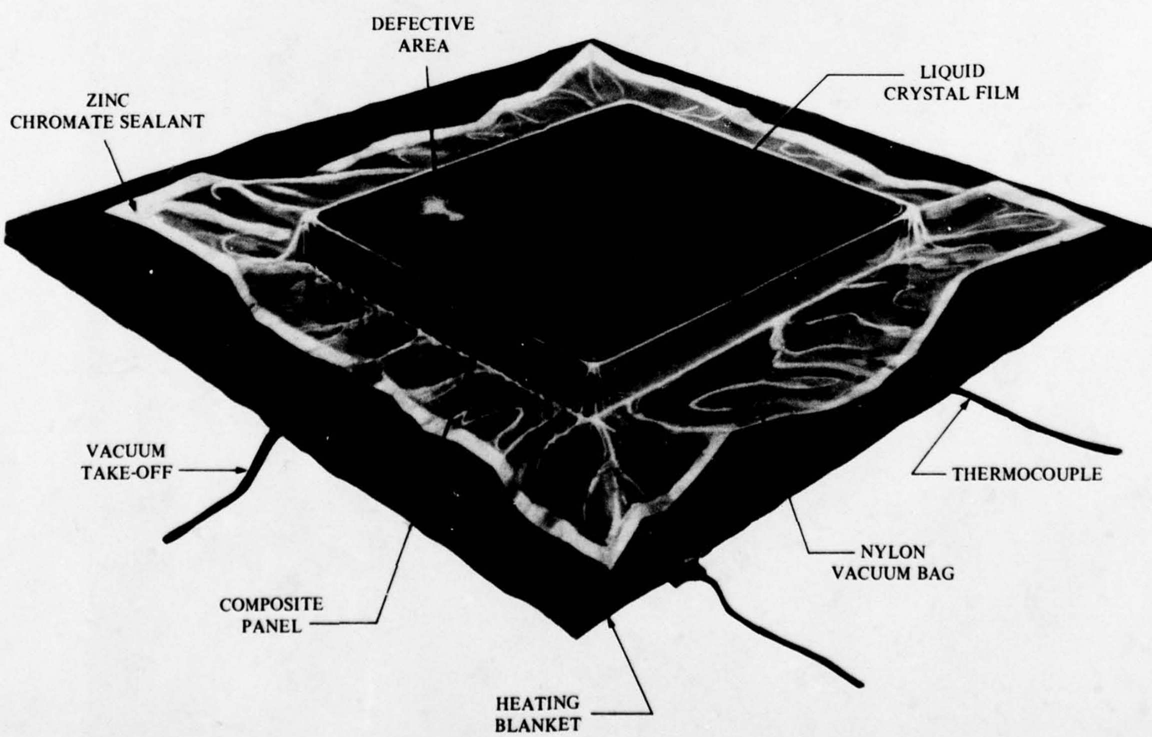

Fig.22 Vacuum bag technique

SESSION III
Part 2: Applications
Rapporteur's Report

by

H.Schnell
VFW-Fokker
Bremen-Germany

The second part of Session III is titled Applications of Non Destructive Inspection Methods in the Field of Composite Materials and Structures. Part one of this session has already shown some application aspects. The general discussion today and yesterday afternoon, I believe, has covered a wide range of NDI techniques as well as the potential applications in this field.

The papers presented this morning are also dealing with both topics: the NDI-techniques and the application of NDI methods. Therefore it may be allowed to give only very brief conclusions of the papers out of my view and then to concentrate on such items not yet discussed.

In the paper presented by Mr Treca it was given a status report and an evaluation outlook of quality control technologies for composite material structures in France. It was pointed out, that the efficiency of both the sonic and ultrasonic methods used up to now for the inspection of bonded structures is limited. Test results obtained in the laboratory give the confidence that the ultrasonic immersion technique and the holographic interferometry are the methods working sufficiently in the future.

In the second paper presented by Mr Maigret it was shown what practice is used at this time to guarantee the reliability of filament wound structures. For the acceptance testing of the raw material as well as for the non destructive testing of semi finished parts and complete structures the present status was described and the way we have to go if we want to improve the inspection testing was pointed out. The efforts have to be directed to the automation and data processing, to the introduction of holographic and acoustic emission methods and to the improvement of physical and chemical test methods for a better understanding of the time behaviour of the matrix resin.

In the last paper presented by Mrs Brown the nature of liquid crystals was defined and discussed and also it was shown how we have to use these crystals in the field of non destructive testing of composite structures. Two different techniques in using the crystals are described: the liquid brush on condition and the solid state in a film. The results obtained by testing several kinds of sandwich structures and complete composite structures were presented. It was pointed out, that this non destructive testing technique is relatively inexpensive, easy to utilize and interpret and completely reliable.

Now, as mentioned before, I would like to pick out some important topics we have not discussed yet. At first in my opinion the acceptance testing of the raw material is one essential point we have to look at. Due to the fact that we cannot improve a composite part by means of NDI we have to assure that the material we use in the fabrication process is in such a condition and of such a quality that we could expect a structure without any faults.

As far as I know the acceptance testing today usually is carried out by means of destructive testing and visual inspection. I think it should be discussed later on what kind of experiences there are in following the way pointed out by Mr Maigret, that means using special physical and chemical methods such as infrared spectrography, micro-calorimetry etc. in this particular field. This discussion should also be carried out under the aspect of costs and economy.

Now there is another argument in the papers to which I would like to give some comments.

The test procedure in general or only for larger composite parts using a two step sequence is introduced. That means, first global detection by infrared thermography followed by individual defect determination with ultrasonics and other methods.

Now, we have heard a lot about test methods and what flaws are possibly detected. As a result there is no NDI method able to work sufficiently in the first, more global, test step in case of general application. For special applications this procedure might give some advantage in cutting off time and costs but we have to take care that the method used for

the more global testing is able to detect those types of flaws reliably you have to find depending on the load and the shape of the structure.

My question is now: Which method the holographic interferometry, the thermography by using an infrared camera or by means of liquid crystals, or the acoustic emission technique is the best for a more global testing depending on a special kind of structure.

Are there some more examples of application?

Now I think I have to cut my report to give space for the general discussion.

DISCUSSION SUMMARY
Session III – Part 2

T.Kearns (US – Session Chairman)
I would like to refer back to M.Maigret's remarks on the control of raw materials. When we describe a metal we give its chemical composition in detail, we specify what trace elements may be present, we specify the grain size, we specify the mechanical properties and finally we have a reasonable description in technical terms of what the metal is. When we describe a resin we order a gallon of Epon 888, and that is about all we know about it. In fact things are worse than that, because that is all the manufacturer knows about it too. He knows the ingredients and he knows what he did with them, but he does not know the molecular weight, he does not know the degree of polymerisation and he does not know the state of bonding, because nobody measures these things. I would therefore like to invite comment on what can be done to advance our capabilities in this direction. Perhaps first we should answer the question Can we tolerate this situation, or should we do something about it? If we have to do something about it, what should we do?

J.P.Maigret (FR)
There is no solution to this problem at present. We have conducted studies very recently in connection with specific problems but I am afraid that they will not have a general application. We must think in terms of each specific case.

C.P.Galotto (IT)
Although I find myself surrounded by engineers I hope I may be allowed to quote the English physicist Faraday who said that science and technology can be either mathematics or a collection of stamps.

Some methods have been explained, but all of them are qualitative and not quantitative, in other words they indicate that something is wrong in the structure but in most cases we cannot see what kind of a defect or how big it is. I know technical journals describe new methods which will have, for example, automatic counting of fringes in holography; I know that in thermography it is possible to put numbers to the intensity of the various colours. I think that these methods are some of the major items to which we should pay attention.

One point which has not been made very clearly is that in NDI we always feed some energy into the specimen and then we measure another form of energy at the output. We need to collate this output energy, which we can measure, with the microscopic engineering property in which we are interested, e.g. corrosion, creep or fatigue. It is not very clear to me what are the relationships between the defects which are detected by these methods and the relevant engineering properties in which we are interested.

T.Kearns (US – Session Chairman)
I plan to organise the discussion in two sections, firstly on the characterisation of the material, and secondly on the significance of defects. *Dr Galotto has pointed out the need for quantitative measurements in relation to the significance of defects.* May I first invite comment on the subject of characterisation, that is to say how are we to describe the materials so that we know what we have in the first place?

R.J.Schliekelmann (NE)
I can only tell you what we do for the incoming inspection and evaluation of organic materials. One very effective method is the automatic torsion pendulum testing of samples. We adopt a temperature range from −60° to 150°C, and measure automatically the change in shear modulus from the damping of a slowly vibrating pendulum. We have found that small changes in the matrix resin of a prepreg show up quite well, so that this signature of shear modulus and damping against temperature is a very good system. We use the same test after exposing the same to a period at high humidity, and if the material is not up to standard, the location of the damping peak changes markedly on the temperature scale. In addition to these tests, we also carry out infra-red spectroscopy which again helps our evaluation. The third test we make on an incoming prepreg is a viscosity test under standard conditions to see how the resin flows out. Whilst these three sets of information do not completely describe the material, they help us to get an idea of its consistency.

T.Kearns (US – Session Chairman)
The torsion pendulum appears to be a sensitive test, but it is nevertheless one in which you are measuring mechanical properties. In the flow test you are measuring viscosity, which can be due either to a uniform concentration of a given molecular weight or a mixture of high and low weights, so the test is not really specific. We have many developments of spectroscopy, including the use of infra-red and ultra-violet rays, providing a large number of potential test methods which are not used very often. Would it not be to our advantage to examine the usefulness of these different test methods to see what kind of signatures they give us, and then decide which one might constitute a good scientific application taking economics into account?

P.R.Teagle (UK)

I am a little disturbed at the impression which has been given that no batch testing is done, particularly in the USA. We base most of our procedures on accepted American practice. Both mechanical and physical tests are performed on incoming composite materials, and I would not like to detract from the value of these mechanical tests. In addition, all incoming resin is checked by thermal analyser techniques so that we measure glass transition temperatures, degrees of cure and the characteristics of the cure by looking at endothermic and exothermic reactions, all of which are carried out on samples of the resin before a batch is accepted. Some of these procedures are agreed independently between ourselves and the suppliers, whilst others are included in a national document (NM547) which was drawn up between prepreg manufacturers and users in the UK. There is of course scope for a great improvement in the acceptance tests for our material, but it is by no means in the state which has just been described.

G.Jube (FR)

I do not think the Chairman gave too pessimistic a veiw of the situation; he has pointed out a very real problem by comparing the knowledge we have of metals and our lack of knowledge of resins. Following what M.Maigret has said, I feel that the methods which make it possible to measure indirectly the qualities of resins are very expensive in the long run. This situation is not acceptable in France at present, and we have set up a committee whose task it is to clarify the composition of resins. The conclusions of this committee will probably be that the only products we shall use will be those whose contents are known.

One further parameter which we measure is tack. Tack is a very important characteristic, and indeed it is so important that we are surprised it is not the subject of more research. Before manufacture we estimate the voids that we shall have, since the less tacky the material the more voids will be present in the finished product. It would be more intelligent for everyone to take these measurements of tack before the component is made, so as to avoid scrapping parts with too high a void content.

At present, however, the measurement of tack is merely subjective. In France we have operators with a calibrated thumb, and they apply this thumb to the product to see whether it is good or not. All the systems that we are aware of for the measurement to tack are gadgets and not scientific instruments. We have systems pushing, pulling, measuring the time required to impregnate the fibre; we roll a ball to determine when it stops, but none of these are a serious scientific approach, and we would like scientists to develop a method for measuring tack so that we can know exactly what happens when you apply your thumb to the product.

J.Quinn (UK)

There have been considerable discussions in the UK on the drawing up of a common resin specification which will lay down the tests which are felt to be necessary to ensure an acceptable matrix resin for composites. One of the difficulties of course is the considerable number of types of resin, and it will be necessary to reduce these to a much smaller number. There would naturally be some resistance from the resin manufacturers, who are always trying to develop new products, but obviously there will have to be a move in this direction.

T.Kearns (US – Session Chairman)

As technical people, we should not have to decide which resin we are going to use in order to make a contribution to our knowledge about what the resin is. I would like to hear the reactions of the audience to this point. Should we tell the SMP that the characterisation of resins is in fact a subject which needs additional attention, and that they should see what can be done to advance our state of knowledge? On the contrary, is there agreement with Mr Teagle that things are going well enough, and the SMP has thus no contribution to make? I am sure the Panel would appreciate any guidance that we can give them in this respect.

P.R.Teagle (UK)

I certainly agree that improvements are necessary. I was merely stating that the situation is nowhere near as bad as has been made out. I believe that the SMP are aware of the problem of standards, both of materials and the test procedures required to define these materials. It must be pointed out that lengthy resin evaluation programmes were undertaken in the early days of composite development to determine the desirable characteristics of resins, and these programmes are leading on to the standardisation process.

S.Hanagud (US)

I agree with the Chairman that there is a great necessity to standardise polymers. My own experience when I first wished to buy a resin from one of the manufacturers was that he would not supply the resin but only prepregged material. When I specifically asked for the resin, he would only supply it with the proviso that I would not make a chemical analysis. We would like to buy the resin from those people who will allow us to make an analysis. In metal structures we find many defects which can cause other failures like embrittlement, stress corrosion and fatigue. In the same way we do not know what we are likely to experience in composites unless we start by knowing the characterisation of the resin.

T.Kearns (US – Session Chairman)

I suggest we now move to the subject of the significance of defects. Each of our speakers has spoken about the process they use to reveal "defects", but I do not think they really meant defects; what they meant was "indications", since a "defect" is a defect only if it is important. We have indications of all sorts when we examine

a composite part, but how do we know whether we should reject the part, accept it or fix it? In metals we establish our specifications not by determining what defects will reduce the service life of the component, but by seeing that it is practical and economical to make material of a particular quality, and therefore we will accept nothing less. With composites, although we get indications, we still have a long way to go to determine which indications are serious defects. Are there any comments on my observations?

G.Jube (FR)

I would like to suggest that the term "destructive" should be regarded as something that has an absolute value. Although we are talking about non-destructive inspection, we must consider the fact that destruction of a component is also necessary, and this is the only means whereby we can find out what the indications mean. This is a practice which we have adopted from the earliest days of bonded metallic components.

We originally sacrificed one panel out of every 10. Although we gradually reduced this frequency, I would like to point out that we know of no other means of calibrating the indications in a quantitative manner. It is possible, with the help of experience, to take into account variations in the indications which reveal a quantitative difference which can be linked with a destructive effect. We must remember there must be a co-ordination of systems in serious production, and it would not be prudent to rely entirely on NDI. Every now and again we must have recourse to the dissection of a laminate, cutting it up into small pieces and studying it under a magnifying glass.

C.P.Galotto (IT)

In many of the techniques we are using today we are measuring an overall factor which can be due to several causes. When we measure attentuation, for example, any variation can be the result of several different causes which we do not analyse in detail. This lack of information, in my opnion, accounts for the fact that our usual procedure is to have a destructive test once in every 10 or 50 components.

T.Kearns (US – Session Chairman)

Judging from what the last two speakers have said, it seems that there is a clearly recognised need for destructive testing in order to understand the significance of defects. Our general conclusion appears to be that this kind of testing should continue, so that with experience we will build up sufficient knowledge to be able to see what is important in given components.

G.A.Darcy (US)

I agree that correlation is very ncesssary, otherwise the measurements can be meaningless. I would like to suggest that NDI is considered earlier in the manufacturing cycle, and that it is not regarded as a negative technique looking for flaws, but is used as a monitor of incoming materials and applied in such a way as to prevent flaws rather than locate them when they happen.

DISCUSSION SUMMARY
Closing Session

W.G.Heath (Meeting Chairman)

This meeting, as its title implies, has brought together not only NDI specialists by also materials producers and aerospace designers to establish the relationships between the various aspects of their jobs. One of the tasks of AGARD is to find gaps in our knowledge so that we can aim research in the right direction; as this meeting has proceeded I have been trying to identify those areas where relationships between these people could be improved, so that the SMP might have some guidance for directing future research. I find it easiest to classify these areas under the headings of three kinds of people: NDI specialists, designers and material producers. There is one other group of people who we ought to interest in this research, because during the meeting a great deal has been said about the human aspect of inspection, and the only specialists who can help are psychologists.

My list is as follows:

1. **NDI Specialists**

(a) *Identify the Gaps and Overlaps in the Spectrum*

This point was made by Mr Schliekelmann and refers to the spectrum of available techniques. There are sources of energy available which will generate waves from the size of an Angstrom to several centimetres in length, and we need to know where these sources fit on the spectrum to identify the gaps and overlaps.

(b) *Quality of Bonds*

In the field of practical applications, the quality of adhesive bonds was mentioned on at least two occasions as a subject of great importance. We can readily determine if a joint is stuck or unstuck, but we cannot measure the degree of adhesion.

(c) *Thick Laminates*

During the composite discussion, it was clear that no answer was forthcoming to the question How do we inspect thick (i.e. of the order of 50 mm) laminates?

(d) *High Cost of NDI of Composites*

When comparing the total price of a composite component against that of an orthodox metallic one, the very high cost of the NDI of composites is often overlooked.

2. **Designers**

(a) *Tell the Inspector Where to Look*

This plea was made on at least three occasions during the earlier sessions. When the inspector knows where to look, then the NDI specialists can presumably tell him how to look. Knowing where to look depends very much on how representative the fatigue test has been; how realistic for instance was the load spectrum, whether the test has been continued for long enough to develop the cracks properly, and so on.

Under this heading a plea was also made on behalf of the aircraft users for better accessibility for inspection.

(b) *Brittle Materials*

Although designers have traditionally fought shy of designing in brittle materials, some NDI specialists appear to be prepared to guarantee to find defects before they can reach a critical size.

3. **Materials Producers**

(a) *Acceptance Standards*

This subject could also be written as the question What is a defect, and when does it become important?

(b) *Characterisation of Resins*

This subject arose during the discussions on composite materials, and is a long standing problem.

4. **Psychologists**

(a) *What Makes a Good Inspector?*

This question was asked several times during the meeting and we had a very interesting discussion on the second day when Dr Jarfall showed how different inspectors using different techniques obtained quite different answers from the same set of cracked specimens. Mr Bond made the point about the relationship between educational standard and the likelihood of finding failures, whilst Mr Forney presented the analogy of the fisherman who is prepared to sit by the water all day but expects to catch nothing.

(b) *Automation*

One of the chief human problems in inspection is that of boredom. The question of whether more automation will help to reduce boredom, or whether it will in fact increase it, is one which could also be referred to the psychologist for an answer.

I.N.Matay (US)

I would like to recommend another heading alongside the designer, and materials producers and the psychologist, and that is the users of the aircraft.

W.G.Heath (Meeting Chairman)

The classification of research areas under the various headings should not be regarded as too rigid. Whilst I accept the users as a further group of people who should be included, all the problems we have discussed are interface problems, the responsibility for which is shared by all the groups of people.

D.M.Forney (US)

I think that NDI specialists have a poor reputation as a technological group. Our reputation is poor with the user because we frequently fail to give him the confidence he needs. We fail with the designer because he feels we don't know what we are talking about, and very often he is right. We fail with the materials producer because we cannot provide him with sophisticated means to characterise his materials. I think that we will continue to suffer from this bad reputation and fail to make an impact on the whole situation unless we do a better job of identifying what is our role as an integral part of the design, manufacturing and management scene.

Our role with the designer is a different one than with the manufacturer or with the user. The type of non-destructive testing methods we would use might be quite different in a manufacturing situation than they would be in the user situation, and we have got to recognize that difference. I think that as a team of people we have to get our economics right. In the history of NDI we have been an undesirable addition to the scheme of things, but I believe that there are many cases where we can make things possible by inspection which the manufacturer currently cannot do. I think we need to exploit this ability and communicate it to the designer and manufacturer.

As an international community, we must establish common development objectives. We must focus our activities, we must share our data, we must pool our resources whether they be money or knowledge. We need to reinforce one another to increase our leverage on the rest of the scientific community. I really think that the time has gone when we can have a successful development programme with adequate resources where we deal with a scientific idea the application of which we have not yet realised. I believe that the only thing which will gain us resources to work on technolgical improvements is that we should identify the problem which needs us and then put together the capability to solve the problem.

Finally, I want to make the point that talking about the sensitivity of our techniques is a good academic exercise, but how good are the techniques on a day-to-day basis when they are in the hands of our ordinary inspectors?

R.J.Schliekelmann (NE)

I think the designer who is used to metal structures expects a composite structure to behave in a similar manner. It is very important that much more emphasis is laid on the viscoelastic properties of non-metallic structures. One big question is whether the fatigue test is a good guide to the behaviour of a composite structure and it may be that flight operation in many parts of the world is the only way in which to prove the serviceability of a composite component.

J.Rowe (UK)

I would like to make a contentious suggestion that a fatigue test is an admission of defeat on the part of our designers. The very fact that we have to rely on the fatigue test is itself an admission of defeat, as is our having to design aircraft from the point of view of inspectability. I would like to see the ultimate aim – perhaps originating at a very high level – of trying to eliminate NDI altogether.

W.G.Heath (Meeting Chairman)

We must now express our thanks to all the people who have made this meeting the success I believe it has been. First of all we must thank our Norwegian hosts who worked so hard – some of them were working to the very last minute building this platform. We have had excellent facilities throughout the meeting and we must not forget the nameless people who provided our bodily comforts during the coffee breaks.

We also remember Dr Galotto and the Conference Committee who have been planning this meeting for the past two years. I am sure you will agree that we owe our thanks for all the hard work which went into its preparation.

We must of course thank the authors and the speakers. We have heard 18 papers from 7 countries, and I think those numbers in themselves show the popularity of this subject throughout the western world.

We also thank everyone who took part in the discussions, and I include especially those who had thought about the meeting beforehand and came with a prepared discussion in their briefcase. This meeting attracted over 100 people from 12 nations, which must be a record in itself.

The meeting was divided into 5 separate sessions, each with its own Chairman and Rapporteur, and so there are 10 further people to whom we owe our thanks, and they came from 9 nations.

Last but not least we must thank our technicians and interpreters, without whom the meeting would not have been possible.

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14. Abstract

Because the existence of poor communications and limited rate of integration among materials technologists, design engineers and NDI experts was realized by AGARD, the Structures and Materials Panel took the initiative of organizing a Specialists Meeting at which 20 papers were presented. These papers covered the state-of-the-art for NDI methods for materials of interest to the aerospace industry, the weak points of some methods used at present, the trends of application of known methods and a few new methods. The situation does not appear to be satisfactory in the fields of composite materials and of ceramic materials for turbine engine hot components where much work remains to be done. In the area of metallic materials, the trend is towards automatic inspection, development of smart sensors and in-process inspection. A few methods (low angle neutron scattering, digitalized infra-red thermography, tomography, acoustical emission, multifrequency eddy currents, very high frequency ultrasonic beam scattering) deserve appropriate consideration.

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